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Construction Engineering Research Laboratory

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DoD Corrosion Prevention and Control Program

Leak Detection for Potable Water Lines at Fort Hood

Final Report on Project AR-F-313 for FY05

Sean Morefield

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Final report

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and MIPR5CROBB1012

Abstract: Thousands of miles of direct-buried water distribution lines are subject to severe corrosion at almost all U.S. Army installations. Leakage of storage tanks and piping systems has been identified as a mission-critical problem. To demonstrate acoustics-based leak-detection technology for the Department of Defense (DoD) Corrosion Protection and Control (CPC) Program, permanent acoustic leak-monitoring sensors were installed on potable water lines at Fort Hood, Killeen, TX, during 24 April – 31 May 2005.

As a result of this work, 25 permanent acoustic leak detection sensors now monitor about 7 miles of potable water lines in remote, little traveled areas, where a water leak would not likely be discovered for a very long time. To retrieve the leak status from the 25 sensors, one method is to use a special radio receiver that can be driven past the sensors periodically, and the other is to use a central computer equipped with cellular telephone modems that retrieve the data automatically.

A few problems were experienced during the project, but all were successfully solved. During the project, lessons were learned about some installation and operation pitfalls that will benefit others who undertake the installation of permanent sensors on pipelines at other Army installations.

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Introduction

This demonstration was performed for the Office of the Secretary of Defense (OSD) under Department of Defense (DoD) Corrosion Control and Prevention Project AR-F-313; Military Interdepartmental Purchase Requests MIPR5CCERB1011 and MIPR5CROBB1012, dated 15 December 2005. The proponent was the U.S. Army Office of the Assistant Chief of Staff for Installation Management (ACSIM). The technical monitors were Daniel J. Dunmire (OUSD(AT&L)Corrosion), Paul M. Volkman (IMPW-E), and David N. Purcell (DAIM-FDF).

The work was performed by the Materials and Structures Branch (CF-M) of the Facilities Division (CF), Construction Engineering Research Laboratory – Engineer Research and Development Center (ERDC-CERL). The Project Manager was Vincent Hock. Carlyle Consulting, Yardley, PA, was contracted through S&K Technologies, Inc., St. Ignatius, MT, under contract number 5014-CARL-001. We would like to thank the principal Fort Hood personnel who provided support and guidance during the site visit: Gary Goodman, Drinking Water Program Manager; Tim McPherson, Clarence Pierce, and Bill Orange of the Utility Shop of the Directorate of Public Works (DPW); and Wayne Tafoya of the Utilities Location Branch of the DPW. Everyone at Fort Hood was generous and gracious in their assistance.

At the time this report was published, the Chief of the ERDC-CERL Materials and Structures Branch was Vicki L. Van Blaricum (CEERD-CF-M), the Chief of the Facilities Division was L. Michael Golish (CEERD-CF), and the Technical Director for Installations was Martin J. Savoie (CEERD-CV-ZT). The Deputy Director of ERDC-CERL was Dr. Kirankumar V. Topudurti, and the Director was Dr. Ilker Adiguzel.

COL Gary E. Johnston was the Commander and Executive Director of ERDC, and Dr. James R. Houston was the Director.

Executive Summary

The tasks accomplished during the Fort Hood leak-detection project included the selection of suitable leak detection equipment; coordination with installation personnel to find an appropriate test section of pipeline; installation of sensors, associated communications equipment, and central computer for processing leak data; assuring continual equipment functionality; and traveling periodically to the installation in order to retrieve data, correct technical problems, and participate in the final project inspection. Lessons learned were documented, and they include information about implementation and operational difficulties that will help others avoid the same issues when implementing the technology elsewhere.

As a result of this work, 25 permanent acoustic leak detection sensors now monitor about 7 miles of potable water lines in remote areas where a water leak would not likely be discovered for a very long time. Two different mechanisms are used to retrieve the leak status from the 25 sensors: one method is to use a special radio receiver that can be driven past the sensors periodically, and the other is to use a central computer equipped with cellular telephone modems that retrieve the data automatically.

Several ancillary problems were identified and addressed during the execution of this project. Errors were corrected in the Fort Hood water line geospatial maps. The need for coordination with the information management and logistics directorates was recognized, especially where ordnance is stored. Refinements were made to the installation's cellular telephone communication network to support the leak detection technology. Finally, sensor failures were detected early and replaced under warranty with improved devices.

During the initial 18 months of operation, the leak sensors discovered two leaks. One leak showed surface water upon visual inspection and was repaired. The other leak showed no trace of surface water and was located in a highly secure area where it was unlikely to be visually detected in a timely manner. That leak was initially found by examining the permanent leak sensor's database, and was later verified by a contractor using a cross-correlation leak location instrument during the final project inspection.

Unit Conversion Factors

Multiply	By	To Obtain
ft	0.3048	meters
in.	0.0254	meters
miles (U.S. statute)	1,609.347	meters

1 Background

Leakage of storage tanks and piping systems has been identified as a mission-critical problem for military installations. Thousands of miles of direct-buried water distribution lines are subject to severe corrosion at almost all U.S. Army installations. The Army's replacement cost for its potable water distribution lines may range from $13 – $100 per foot. The cost of a typical leak repair may range from $10,000 to $50,000 per leak due, in large part, to trenching operations that are required to locate the source. The most common method for locating leaks involves excavation of the surrounding area. Of the several new leak-detection technologies tested both in the laboratory and in the field, one of the most promising is acoustic emission technology co-developed by the U.S. Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) with Carlyle Consulting, Yardley, PA.

Fort Campbell prototype

A prototype of this acoustics-based leak-detection technology was demonstrated at Fort Campbell in 2002 to detect leaks in a deluge sprinkler system used for fire protection in aircraft hangars. The subject deluge system had catastrophically failed due to corrosion, impacting all installation flight operations. Proficiency training, and potentially deployment, was affected until the system could be repaired. Fort Campbell requested that ERDC-CERL use acoustic emission technology to locate the leaks in the deluge system within 24 hours. This task was accomplished and flight training resumed.

The Fort Campbell deluge system had failed due to localized corrosion at less than 50 percent of its design lifetime. The demonstrated acoustic leak detection technology provides effective monitoring that will detect costly leaks early in a large, critical distribution system. System operation and maintenance costs are much higher when leaks are not detected and repaired promptly.

Fort Hood demonstration

To demonstrate acoustics-based leak-detection technology for the Department of Defense (DoD) Corrosion Protection and Control (CPC) Pro-

gram, permanent acoustic leak-monitoring sensors were installed on potable water lines at Fort Hood, Killeen, TX, during 24 April – 31 May 2005. The lines are on the West Fort Hood portion of the installation. After the sensors were installed, four follow-up visits were made to Fort Hood to brief personnel, gather periodic data, address some problems, and assist in the final project inspection.

The equipment demonstrated at Fort Hood consisted of four components: PermaLog, PermaCom, Patroller units, and an Xmic were used to collect and transmit leak information.

The PermaLogs installed at Fort Hood are permanent leak sensors made by Fluid Conservation Systems. The PermaLogs use an unlicensed radio frequency band (463.9125 MHz), and were approved in writing by Directorate of Information Management (DOIM) and Directorate of Logistics (DOL) for use in West Fort Hood. Each of the PermaLogs is about the size of a 12 oz. can of soda, and has a magnet on the bottom that allows it both to hold tightly to the pipeline and to acoustically couple any tiny leak sounds propagating through the pipe into the PermaLog.

Three of the PermaLog sensors at West Fort Hood are equipped with special equipment known as PermaComs, which allow the PermaLog data to be uploaded into a central computer without human intervention via cellular telephone modems. Many different retrieval schedules can be set up, but the one that worked well at Fort Hood was a weekly upload at 0900 Sunday morning.

Information is retrieved from the PermaLog sensors using a special radio receiver called a Patroller. This device is taken by vehicle into the vicinity of the PermaLogs, and their acoustic leak data are retrieved automatically. The retrieval takes place quickly; at West Fort Hood, the drive takes only 45 minutes, and vehicle speed limits rather than any technological issue were primarily responsible for the time expended.

Occasionally, another acoustic instrument, a Fluid Conservation Systems Xmic, was used at Fort Hood. This instrument consists of a battery powered control console, a “ground microphone” sensor, and headphones. This type of sensor can detect sounds coming through the ground and can be used to find the exact spot along the pipeline where the leak sounds are the loudest. The instrument lets the user amplify the leak sounds to a

plainly audible level, and also allows the user-set filters to eliminate distracting background noises (such as vehicle traffic or pumps). At Fort Hood, the Xmic "ground microphone" capabilities were used to confirm the location of leaks detected by the PermaLog sensors.

2 Lessons Learned

Some of the lessons learned during this project are procedural and may vary from site to site. Other lessons were related to system installation, where simple changes could improve hardware reliability, data collection, and ease of data interpretation. One of the equipment installation lessons relates to integration of the leak detection equipment into a supervisory control and data acquisition (SCADA) system.

Procedural

Procedural lessons that were learned include the following:

- Start the approval process with the Fort Hood Directorate of Information Management (DOIM) and Directorate of Logistics (DOL) well in advance of the installation process.
- As explained in Chapter 3, the PermaLog and PermaCom radios, even though they do not require a license to operate, can cause security and/or safety concerns. Most military installations now sweep for transmitters, and transmitters that are unapproved are removed quickly and sometimes very roughly. Furthermore, munitions located within access control points (ACPs) may have radio-sensitive fuses, so it is necessary to know before the deployment of any radio system if there is any danger that such munitions could be affected by transmissions from the units.
- Obtain prior approval to dig at the locations necessary to install the PermaLog and PermaCom units. Communication cables, fiber optic cables, gas lines, etc., sometimes run close to water pipelines, and it is important to be certain that digging will not cause damage to these cables or pipelines. Furthermore, the excavation necessary to install the PermaLog and PermaCom units might damage vegetation important to the survival of endangered species, or damage sites of scientific or historical interest. Normally all of these concerns will be addressed during the process of obtaining a digging permit.
- Obtain good mapping information and a means of easily tracing pipes through the ground. Pipeline maps are sometimes in error for a variety of reasons ranging from poor surveying to field repairs. The GIS maps at Fort Hood were for the most part quite accurate, but as explained in Chapter 3, problems were encountered in locating five sensors. The use

of multi-spectral maps made it possible to find trench lines that marked the true route of the missing pipelines (see Figure 1). Also, the use of radio frequency (RF) pipe location equipment, such as that shown in the foreground bottom right in Figure 2, proved invaluable.

System installation

Lessons related to installation process include both sensor deployment planning and physical installation concerns. Pumps can make the interpretation of leak data difficult. Yet it is important to obtain leak detection coverage in the vicinity of pumps. At the site of one pump, the PermaLog units closest to the pumps were intentionally spaced almost the same distance from the pump that the PermaLog units were spaced apart on the pipeline route itself. In another area, the PermaLog units closest to the pump were spaced only half the distance that PermaLog units were spaced apart on the pipeline route, but this closer spacing did not work as well. The leak data obtained by those units could have been interpreted more easily had a wider spacing been used.

Because of equipment cost for the PermCom units, the most likely method for data retrieval will be using the Patroller, which needs to be driven near the vicinity of the PermaLog units. The distance over which the Patroller could hear the PermaLog units was dramatically improved by installing better external antennas and by using all plastic components for the sensor housings, sensor housing cover, and vertical riser pipe. The normal PermaLog antenna is the short black rod on the top of the PermaLogs, as shown in Figure 3. When the PermaLog is installed on a pipeline, this antenna is well below ground level; therefore, it has a restricted transmission range on the order of 25 to 50 ft. A longer dipole antenna (seen at the top of the bottom right photograph in Figure 4) was used instead, mounted above the surface of the ground inside the plastic sensor housing. Mostly, transmission ranges of up to about 1,000 ft were obtained, but in one case, data were consistently obtained from a PermaLog unit that was 6,600 ft from the Patroller.

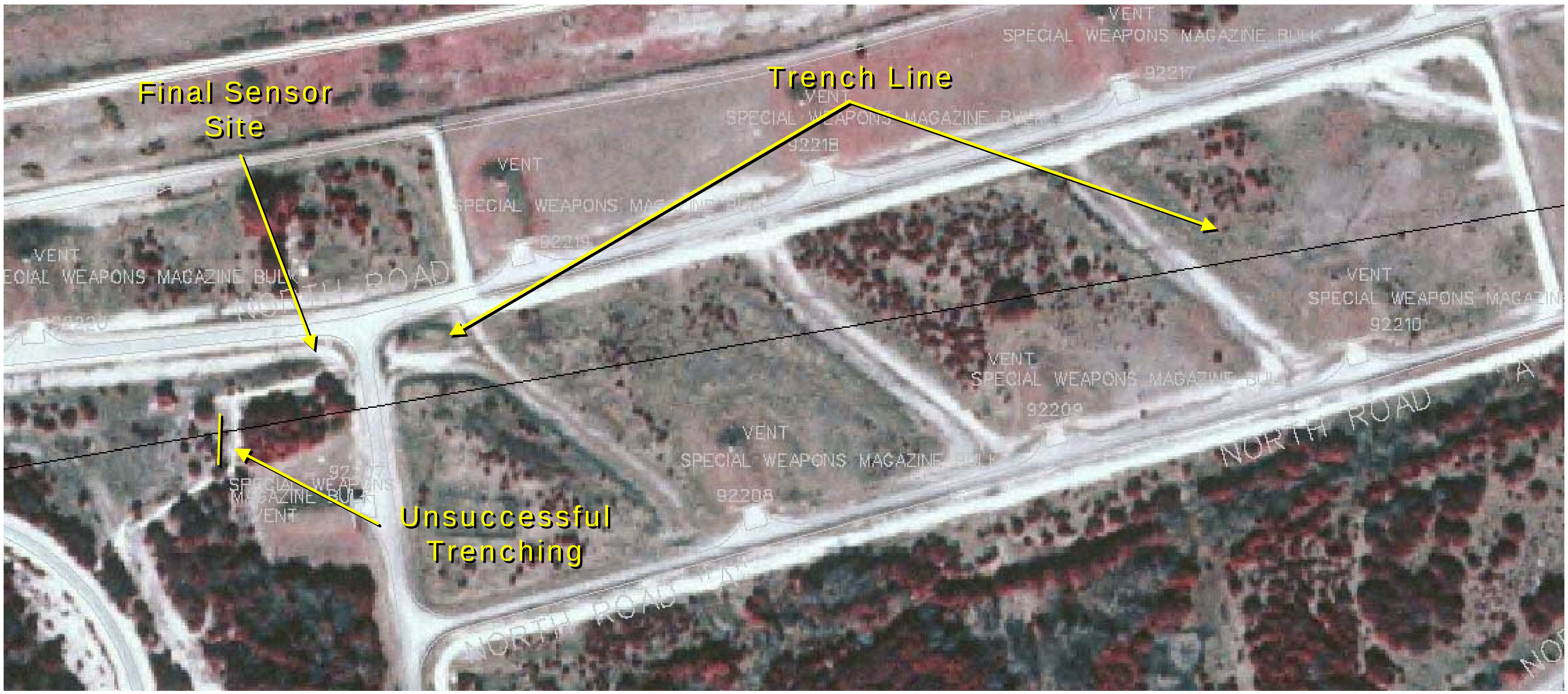

Figure 1. Showing how the false color multi-spectral maps reveal the actual route of the pipeline. Also showing how the actual pipeline route (light gray line) is different from the GIS map indicated route (black line).

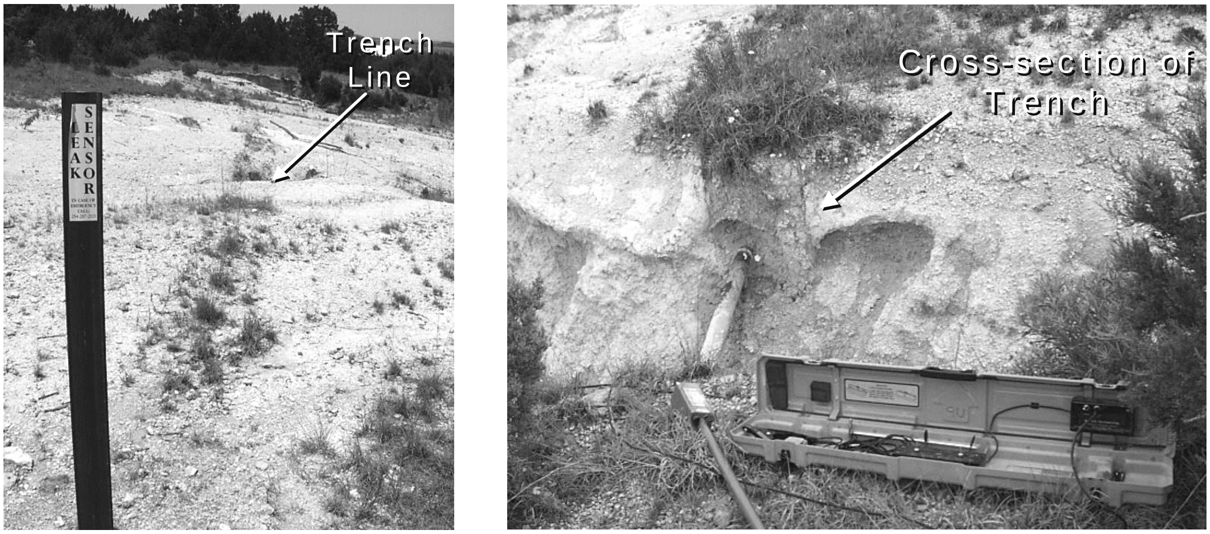

Figure 2. (Left) Showing how vegetation can reveal a trench line. (Right) Showing the backfill that causes different vegetation growth, as well as an RF pipeline location instrument.

Figure 3. Showing 10 PermaLog leak sensors with a Patroller data retrieval unit.

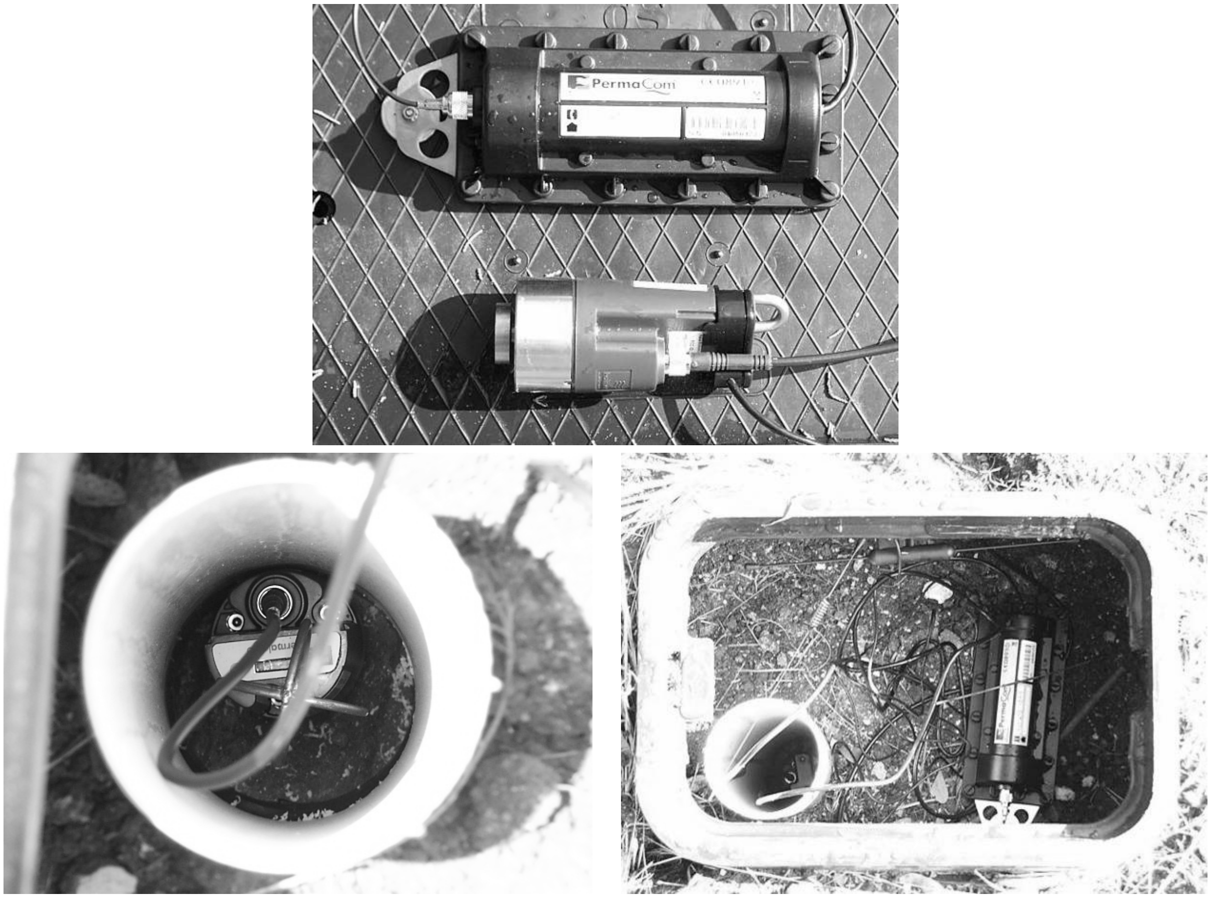

Figure 4. (Top) Showing the blue PermaLog sensor and the black PermaCom unit. (Left) Showing the PermaLog sensor on the pipeline at the bottom of the vertical riser. (Right) Showing the PermaCom inside the leak sensor housing.

The PermaLog units can be used while they are submerged in water. However, some failures occurred with PermaLogs that were under water. A high water table cannot be helped, but in some cases at Fort Hood, it was discovered that the rubber boot seal at the water pipe allowed water to accumulate in access ports for long durations. The problem occurred at the bottom of the vertical riser pipes, as shown in the middle-left photograph in Figure 5. The rubber boot had been specified because it was felt that it would prevent the backfill dirt from entering the riser pipe and covering the pipe surface, which would have prevented proper acoustic coupling between the PermaLog and the pipe. This expectation was met, but when it rained, the water was unable to drain out of the bottom of the vertical riser because the boot was sealed to the pipeline. For future installations, it is recommended that a plain plastic vertical riser pipe be used and a single sheet of newspaper be taped to the bottom of the pipe in place of the rubber boot. This substitute will keep the backfill dirt out, but the newspaper will disintegrate when it gets wet and allow rainwater to drain away.

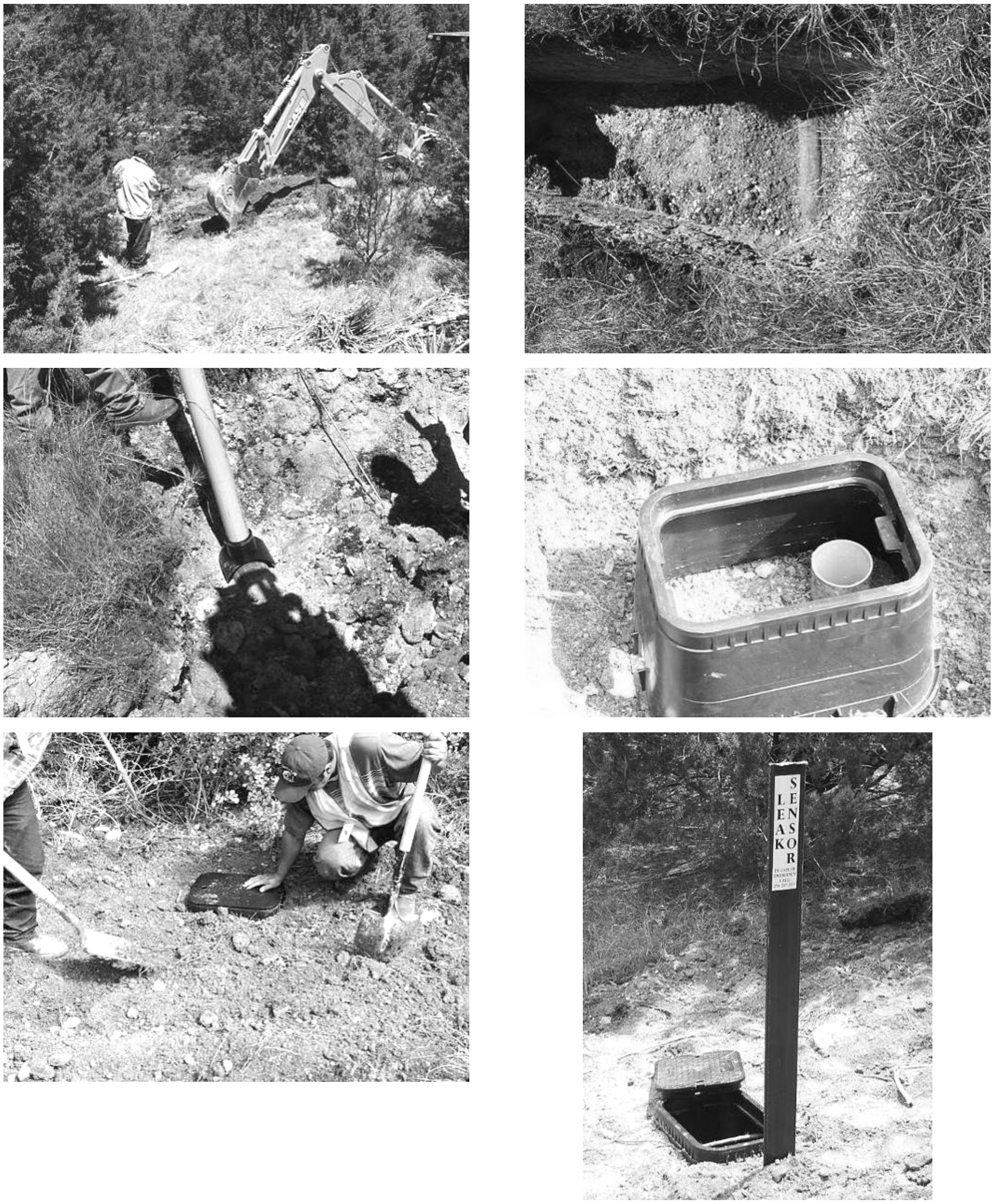

Figure 5. The excavation of the pipeline, the exposed pipeline, the vertical riser pipe with rubber saddle, the sensor housing with vertical riser inside, backfilling the housing, and the finished sensor housing with cover and marking stake.

Another installation issue concerned the cover of the sensor housing. These covers come with a 1 in. diameter hole to permit easy removal. That hole permits easy access to insects, mice, and snakes. Although no damage occurred during the demonstration, it is possible that mice could gnaw through the antenna cables. During the demonstration, bees had made a honeycomb inside one sensor housing, and the sensor subsequently failed. It is not known whether the honeycomb caused the sensor to fail, but it was a real problem removing the cover, removing the bees, and replacing

the PermaLog unit. All of the holes in the covers were plugged to prevent further such occurrences.

One of the reasons that the PermaCom units were installed was to automatically retrieve data in order to demonstrate the feasibility of interfacing the leak detection system into a SCADA system. The idea appears to be possible, but it could not be fully tested because Fort Hood does not have a SCADA system. The problem to be addressed is one of data interpretation rather than simple data access (see Table 1). For any given day (shown in columns in Table 1), a SCADA system would show that up to ten PermaLog sensors were detecting leaks when only two actual leaks were present. Simply connecting the PermaLog leak sensors into a SCADA system would probably create problems but not help much to ensure a tight potable water system without some method to show sensor history and to automatically factor out the influence of pump noise. At the moment, however, this is not possible.

Table 1. Leak monitoring results at Fort Hood.

Sensor	28-May-05	29-May-05	30-May-05	10-Jul-05	11-Jul-05	30-Aug-05	31-Aug-05	12-Dec-05	13-Dec-05	8-Jun-06	9-Jun-06
LS 1	13	7	14	10	13	0	12	4	6	3	3
LS 2	6	11	8	17	15	20	17	17	19	19	21
LS 3	14	17	14	13	15	20	28	10	14	24	18
LS 4	**28**	**27**	**36**	16	16	**23**	17	x	x	**28**	**22**
LS 5	**21**	**22**	**22**	**22**	**34**	**56**	**56**	**56**	**56**	**27**	**22**
LS 6	**33**	**34**	**33**	**33**	**50**	**50**	**47**	**37**	**41**	**42**	**37**
LS 7	**27**	**26**	**27**	**34**	**33**	15	11	**38**	**36**	**34**	**27**
LS 8	**24**	**19**	**24**	**25**	**19**	**19**	**56**	22	21	**57**	**57**
LS 9	11	12	12	12	12	12	7	10	10	14	7
LS 10	14	16	15	8	9	10	11	14	11	**47**	**56**
LS 11	15	16	10	8	7	8	11	15	12	9	12
LS 12	14	15	16	11	6	9	9	10	11	15	13
LS 13	7	6	7	4	4	9	9	6	4	9	10
LS 14	10	10	10	14	14	13	12	6	4	10	9
LS 15	4	4	4	5	5	7	7	4	4	5	5
LS 16	**24**	**24**	**24**	**28**	**29**	**35**	**33**	**28**	**28**	**28**	**28**
LS 17	**61**	**58**	**61**	**54**	**53**	**55**	**33**	**58**	**58**	**54**	**47**
LS 18	**44**	**43**	**44**	**44**	**41**	**41**	24	**41**	**37**	**42**	**32**
LS 19	**36**	**32**	**36**	**36**	**30**	**36**	21	**36**	**31**	**57**	**39**
LS 20	**31**	**32**	**32**	**31**	**31**	**30**	**30**	**37**	**36**	**37**	**34**
LS 21	**27**	20	26	13	11	10	6	14	13	**46**	**46**
LS 22	5	4	4	5	5	3	4	3	4	5	4
LS 23	6	6	6	6	6	9	6	4	6	6	5
LS 24	5	5	5	6	7	10	10	12	12	13	12
LS 25	9	10	10	10	10	18	17	9	9	15	15

Notes: LS16 shows a leak, as does LS20. LS4 through LS8 are under the influence of a pump located between LS6 and LS7. LS17 through LS21 are under the influence of a pump near LS17. Yellow area indicates an 8 in. line; blue area indicates a 3 in. line; tan area indicates another 8 in. line, and green area indicates a 2 in. line.

3 Technical Investigation

Equipment installation

The installation of the permanent leak sensors at Fort Hood started with the writing of a detailed project plan. Carlyle Consulting distributed this plan to all involved personnel at both Fort Hood and ERDC-CERL 1 month before sensor installation began. The project plan:

- described the purpose of the work
- set forth the work schedule
- listed the sensor locations by global positioning system (GPS) coordinates and depicted them on maps of the pipelines
- gave warning that there was a need for restricted area access; gave a extremely detailed work procedure
- included a health and safety plan, a communication plan, and an environmental impact plan.

No comments were received on the project plan prior to the arrival of Carlyle Consulting personnel at Fort Hood. On 25 April 2005 the work plan was formally presented to all involved personnel at Fort Hood. At that time, installation personnel identified three potential problems that could delay or stop the project:

1. All of the leak sensors and the central computer needed to be approved by DOIM, a process which was estimated to require 6 months (because of risk management).
2. The leak sensors, since they had radios, needed formal approval by DOL before they could be installed in locations inside the ACP areas (because of concerns about munitions fuses).
3. The digging permit paperwork for all 25 sensor locations had to be submitted and approved by several Fort Hood offices before any sensor location surveying could start.

Following the work plan presentation, contractors met with the Directorate of Public Works (DPW) DOIM representative. He explained the information requirements for the central computer (model, operating system, purpose, location, the fact that it would be stand-alone and would not connect to the Fort Hood network) and for the leak sensors (type and

model of sensors, proposed locations, cellular telephone numbers, service providers, anticipated use for equipment, installation timeline, the fact that they would not connect to the Fort Hood network). A report entitled “Information for DOIM Regarding the Fort Hood Permanent Leak Detection System” was written and provided to the DPW DOIM representative on 28 April 2005. Approval to proceed with the installation of equipment was formally granted by DOIM on 5 May 2005.

A process similar to the DOIM sensor approval was started with DOL to gain approval to install the sensors inside the ACP areas. First, Frank Brantley of DynCorp explained the type of information required (type sensor, proposed location, operating radio frequency, total radiated power, and maximum transmission distance). An e-mail entitled “Leak Detection Sensor Specifications” was written and sent to Brantley on 27 April 2005, providing him with this information. He forwarded the email, and DOL formally granted approval on 3 May 2005.

To start the digging permit paperwork, a meeting was held with Duane Turner of Shelton and Shelton Plumbing on 25 April 2005. The necessary Fort Hood forms were taken so Turner could fill them out. An important part of the digging permit was the maps, which showed approximate positions along the various potable water pipelines where sensors were proposed to be located. After Turner signed the permit, the form was hand carried to the three different offices at Fort Hood that needed to approve the permit. The fully signed digging permit was then dropped off at the Utilities Location Branch of the DPW that afternoon.

Informal surveying of the sensor locations also started on the afternoon of 25 April 2005. Team members drove to West Fort Hood with their sensor location maps and list of GPS coordinates for the sensors, both of which are shown in Appendix A. First a magnetometer was used to locate the route of the pipeline near the area of a proposed sensor, and then a handheld GPS was used to locate the exact point along the pipeline where the sensor was to be located. In 2 hours, the locations for sensors 4 through 10 had been marked with flags.

On Tuesday, 26 April 2005, the formal surveying and location approval work started with members of the Utility Location Branch and the DOIM joining the contractors. The process followed was to again use the magnetometer to locate the pipeline, use the GPS unit to find the exact sensor lo-

cation, and use flags to mark the spots. At the end of 2 days of work, formal digging approval had been obtained for 20 of the 25 leak sensor locations. Four of the remaining locations were inside secure areas and were inaccessible that day. For the last sensor location, the magnetometer simply was unable to locate the pipeline.

Digging for the installation of the sensor boxes started Saturday, 30 April 2005. The installation process is depicted in the six photographs shown in Figure 5. In 7 hours of work, vertical riser pipes (leading from the buried pipeline to the surface) were installed at 14 sensor locations. Disappointingly, contractors were unable to expose the pipeline with digging at two of the sensor locations, in spite of extensive trenching. It was discovered later that the Fort Hood water line GIS maps had some errors. In five places where sensors needed to be placed, the pipelines did not run where the GIS maps indicated. Compounding the difficulty, four of these locations were inside secure areas.

The next several weeks involved gaining access to three secure areas and with locating the true route of the potable water lines in five locations. A breakthrough occurred when a Fort Hood naturalist brought into the field false-color multi-spectral maps of the vegetation on the installation, which helped him identify tree species. At one proposed sensor location, the map also showed the actual trench line for the pipeline, due to a difference between vegetation over the trench and next to the trench. The actual pale trench line can be seen in Figure 1, while the reason for the trench line growing different vegetation from its surroundings can be seen in Figure 2.

The Public Works GIS branch was able to overlay the necessary multispectral maps on the contractor’s electronic potable water pipeline maps of Fort Hood, thus allowing the contractors free access to the field at any desired location or degree of magnification. In addition, borrowed pipe location equipment (see Figure 2) allowed a pipeline’s route to be traced by inducing an RF carrier into the metal line. Contractors traveled to each of the newly revealed trench lines, confirmed the presence of the pipeline with a magnetometer, and placed the RF transmitter over the pipe. Then, by simply walking with the RF receiver, the actual route of the pipeline could be traced through heavily wooded areas. Figure 1, Figure 6, and Figure 7 show the errors discovered in the GIS maps for five pipelines. In some cases, it was found that the actual pipeline route was more than 500 ft from where the GIS maps placed it. In 2 days of work,

Figure 6. Showing an example of how the actual pipeline route (orange line) is different from the GIS map indicated route (black line).

Figure 7. Showing another example of how actual pipeline routes (red, light blue, and orange lines) are different from the GIS map indicated route (black line).

all five of the remaining sensor positions were located, and by 18 May 2005 all 25 sensor housings had been installed.

Thirteen PermaLogs were installed on 17 May 2005, while the pipeline location and sensor housing installation work was still in progress. A close-up of the PermaLog leak sensor and its installation on a pipeline is shown in Figure 4. Initial leak data were received from all 13 sensors the next day by driving the Patroller near them, a process that is described in detail in Appendix B. The leak data in the Patroller were then uploaded to the central data computer for analysis, as described in detail in Appendix C. Surprisingly, PermaLog sensor 16, located inside a secure area to which acess was extremely difficult, could be interrogated by the Patroller from over 6,600 ft away on a public road. The Patroller could also, from public roads, interrogate the other four sensors located in secure areas. On 19 May 2005, the remaining 12 PermaLogs were installed into their new housings.

The next task consisted of installing the PermaComs at three sensor locations and the necessary cellular telephone modems at the central data computer. Figure 4 shows a PermaCom unit and its installation inside a sensor housing. Three locations that were geographically diverse and not inside secure areas were chosen as places to put the PermaComs (sensor locations 9, 15, and 22). The hardware installation went smoothly and was completed on 20 May 2005. However, the team was not able to get the PermaComs and the central computer's PermaHost program working to the point that they would communicate and obtain leak data automatically. Resolving this problem took more than a week of telephone calls between the contractors, the manufacturer's representative in Ohio, and the manufacturer's software engineer in the United Kingdom. At the end of that period, sensors 15 and 22 were reporting leak data properly via the PermaCom/PermaHost interface, but sensor 9 was still not reporting before the contractors had to leave on 31 May 2005. Fort Hood arranged an onsite visit from the UK software engineer, which took place in August 2005. As of August 2005, all sensors were fixed and operational.

A formal out-briefing on the project was contractually required prior to the completion of the leak sensor installation visit on 31 May 2005. However, schedule conflicts for Fort Hood personnel led to the postponement of the out-briefing until July. During a 1-day visit to Fort Hood on 11 July 2005, the contract team gave the leak sensor project out-briefing to personnel from Fort Hood and ERDC-CERL. Possibly the most important result of

the out-briefing was to advise Fort Hood that they now had the capability to obtain leak data at any time from all 25 leak sensors, using the Patroller data retrieval method. The Patroller leak data retrieval method had been demonstrated to both Tim McPherson and Gary Goodman of Fort Hood on 23 May 2005, when they both agreed that it was very easy to perform by following the detailed instructions and using the map in Appendix B.

On 30 and 31 August 2005, contractors again traveled to Fort Hood to meet with Jason Hanlon, the Managing Director of the UK manufacturer of the PermaCom/PermaHost hardware and software. At the time of this visit, none of the three PermaCom equipped sensors were sending their data to the central computer — the two that had been sending data had stopped. Several days of intensive work followed, during which it was determined that two of the PermaCom interfaces to their PermaLogs had failed, that one of the PermaCom units itself had failed due to water ingress, and that the PermaCom antennas were not working properly with the cellular telephone service provider. New antennas, a new PermaCom unit, and two new interfaces were installed, and the software initialization process was repeated. For the first time data were received from all three PermaCom-equipped leak sensors by the PermaHost program running on the central data computer. The UK PermaCom representative was asked about the peculiarities of the PermaHost program that had been discovered. Described in Appendix D, these peculiarities are still pending resolution.

Another visit was made to Fort Hood on 12 – 14 December 2005 to fulfill a contractual commitment for Carlyle Consulting to obtain Patroller data from all 25 PermaLog sensors. Everything was working correctly, and it was found once again that the three PermaCom-equipped leak sensors were reporting values that were identical to the Patroller data for the relevant sensors (see Table 2).

Another visit made to Fort Hood 7 – 10 June 2006 was for the dual purposes of fulfilling another contractual commitment by Carlyle Consulting to obtain Patroller data from all 25 sensors, and to have the final project inspection by OSD, ACSIM, ERDC-CERL, and Fort Hood personnel. Leak data were again successfully obtained with the Patroller, and the PermaLog/PermaHost system was also working well.

The final project inspection by OSD, ACSIM, ERDC-CERL, and Fort Hood personnel started with a briefing of the project, describing the installation process and showing the leak data that had been obtained over 18 months. The briefing was followed with a driving tour, during which data were retrieved from all 25 of the sensors using the Patroller while OSD, ACSIM, ERDC-CERL, and Fort Hood personnel viewed the process. A highly secure area, where the data from PermaLog sensor 16 had indicated the presence of a leak, was then accessed. At this site, no evidence of a leak was found at the surface, but the use of the AccuCorr and the Xmic instruments proved to everyone there that a buried leak was present. The AccuCorr produced an unmistakable result (Figure 8) about 6 ft from a deeply buried shutoff valve, and listening with the Xmic made the sound of the leaking water obvious.

The permanent leak sensors installed at Fort Hood were made by Fluid Conservation Systems, and are known as PermaLogs. The PermaLogs use an unlicensed radio frequency band (463.9125 MHz), and were approved in writing by DOIM and DOL for use in West Fort Hood. Figure 3 shows ten PermaLog sensors and their drive-by data retrieval unit. Each of the PermaLogs is about the size of a 12 oz. can of soda, and has a magnet on the bottom that allows it both to hold tightly to the pipeline and to acoustically couple any tiny leak sounds propagating through the pipe into the PermaLog.

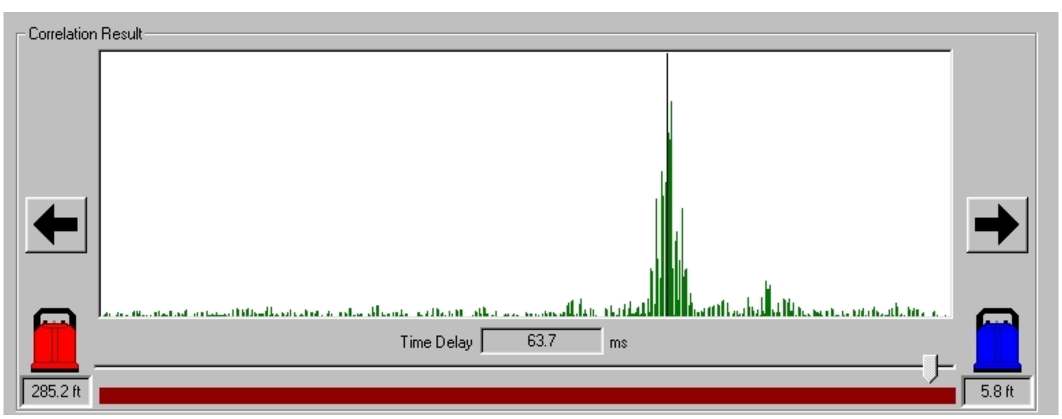

Figure 8. Showing the AccuCorr verification of a hidden underground leak 5.8 ft from a buried shutoff valve. The leak was first detected in the PermaLog data set received from sensor 16. Absolutely no surface water was visible from this leak.

Table 2. Comparison of data retrieval results at Fort Hood.

Sensor	Source	28-May-05	29-May-05	30-May-05	10-Jul-05	11-Jul-05	30-Aug-05	31-Aug-05	12-Dec-05	13-Dec-05	8-Jun-06	9-Jun-06
LS 9	PermaLog	11	12	12	12	12	12	7	10	10	14	7
	PermaCom	11	12	12	*	4	*	7	10	10	14	7
LS 15	PermaLog	4	4	4	5	5	7	7	4	4	5	5
	PermaCom	4	4	4	*	*	*	7	4	4	5	5
LS 22	PermaLog	5	4	4	5	5	3	4	3	4	5	4
	PermaCom	5	4	4	*	*	*	4	3	4	5	4

* PermaCom Hardware Problem Experienced (no data)

Note: Except for the periods when hardware difficulties were being experienced, the agreement is exact between the two data retrieval methods.

Each PermaLog contains a clock that instructs the unit to start listening for 5 minutes at 0200 every night. If leak noises are heard, the unit will again listen for 5 minutes at 0300, and if leak noises are still heard it will listen once more for 5 minutes at 0400. During any listening period, if no leak noise is heard a “no leak” entry is made. If leak noise is heard during all three listening periods, though, a “leak detected” entry is made. This logic allows the PermaLog to reject noises from transient flows, such as water pumps cycling on and off, or flushing toilets. The acoustic data are stored inside the unit for 24 hours, when it is overwritten by the next night’s data. Actual data collected from the 25 PermaLogs during the project are shown in Table 1.

The listening range of a PermaLog depends upon the ambient noise around the pipeline where it is installed. Because the PermaLogs were being installed in remote areas of West Fort Hood where no air or ground traffic occurs at night, they could be spaced about 1,500 ft apart, although some adjustments were made in the vicinity of pumps.

Information is retrieved from the PermaLog sensors using a special radio receiver called a Patroller. This device is taken by vehicle into the vicinity of the PermaLogs, and their acoustic leak data are retrieved automatically. The retrieval takes place quickly; at West Fort Hood the drive takes only 45 minutes, and vehicle speed limits rather than any technological issue were primarily responsible for the time expended.

Three of the PermaLog sensors at West Fort Hood are equipped with special equipment known as PermaComs, which allow the PermaLog data to be uploaded into a central computer without human intervention via cellular telephone modems. Many different retrieval schedules can be set up, but the one that worked well at Fort Hood has been a weekly upload at 0900 Sunday morning. It should be noted that a PermaCom interrogates its attached PermaLog daily, and stores up to 14 days of leak data in its memory. So if cellular telephone communications are not established one weekend, the entire 2 weeks of leak data will be retrieved the next weekend. When both devices returned data, the PermaCom and the PermaLog data sets are identical (Table 2).

Once the PermaLog sensors have detected the presence of leaks, another acoustic instrument, a Fluid Conservation Systems AccuCorr, is used to precisely locate the leak on the pipeline. The most attractive features of

this instrument for the West Fort Hood pipelines were its battery power and its wireless connections between the magnetically coupled sensors and the instrument base, which greatly simplified field use. A technical description of the process used for locating leaks in the field is given in Appendix E. The AccuCorr operates in the frequency range of 1 to 5,000 Hz, and uses cross-correlation techniques to obtain a Δt value to locate leaks. Cross-correlation compares the shape of a signal received by sensor 1 with that received by sensor 2 for all possible arrival times by shifting them in time and adding the two signals together, yielding a single value for each possible arrival time. This processing provides a distinct peak when the time shift of the signals equals the exact time that a signal feature of a certain shape received at sensor 1 arrives at sensor 2. Cross-correlation is sensitive to dispersion (when the shape of the signal changes with propagation, the comparison gets worse), but it has a good track record in the field.

Occasionally, another acoustic instrument, a Fluid Conservation Systems Xmic, was used at Fort Hood. This instrument consists of a battery powered control console, a “ground microphone” sensor, and headphones. This type of sensor can detect sounds coming through the ground and can be used to find the exact spot along the pipeline where the leak sounds are the loudest. The instrument lets the user amplify the leak sounds to a comfortable level, and also allows the user-set filters to eliminate distracting background noises (such as vehicle traffic or pumps). At Fort Hood the Xmic’ “ground microphone” capabilities were used as still another confirmation of a leak location detected by the PermaLog sensors.

Leak detection ability

The ability of the permanently mounted PermaLog leak sensors to find leaks in the potable water pipelines of West Fort Hood has been demonstrated to be quite good. Two leaks were discovered during the project using the data collected by the PermaLogs.

The basic premise of acoustic detection of leaks is simple: when water under pressure leaks from a pipe, it creates turbulence. The sound waves generated by the turbulence propagate in the water down the pipe in both directions from the leak, creating slight vibrations in the wall of the pipe as they travel. A special sensitive microphone, acoustically coupled to the pipe, can detect these vibrations and capture them as electrical signals.

The problem is that events other than leaks can also generate sound inside pipes. Normal use of the water inside the pipeline, such as opening and closing faucets or flushing toilets, creates noise, as does the use of pumps to distribute the water through the system. Furthermore, environmental noises, such as truck, car, or train traffic passing over or near the pipelines, or even airplanes flying overhead, can also create vibrations in the pipeline that are captured by the system as noise.

To detect leaks in the presence of these masking noises, the PermaLogs use two simple facts: (1) normal use of the water system as well as vehicle traffic is much lower during the nighttime hours than during the day, and (2) leaks make noise constantly after they form.

Table 1 shows the data obtained from all 25 PermaLog sensors on various days during the project. The leak values from each PermaLog appear in their own row, with individual days shown in every column. The yellow block contains the results from sensors 1 – 10, which are on the main 8 in. line leading into West Fort Hood. The blue block contains the results from sensors 11 – 16, which are on a 3 in. line leading through an ACP area into a highly secure area. The tan block contains the results from sensors 17 through 21, which are on another 8 in. line leading to a water tower. The green block contains the results from sensors 22 – 25, which are on a 2 in. line leading through another ACP area into a remote building.

PermaLog sensors that indicate possible leaks in the West Fort Hood potable water system are shown in boldface type (Table 1). At first glance, a number of leaks appear to be present in the yellow, blue, and tan pipelines. However, this is not the case. Only two true leaks are being indicated, at sensors 16 and 20. The other 25 leak sensors are being fooled into reporting leaks by the presence of two continuously running pumps. One of these pumps is located on the yellow 8 in. line, between sensors 6 and 7, and its noise propagates up and down the 8 in. pipeline. The pump makes enough noise that sensors 5 – 8 can detect it. Sensors 5 and 8 are about 2,600 ft from the pump, and therefore the pump noise is weaker than it is at sensors 6 and 7, which are only about 1,100 ft distant from the pump. As seen in Table 1, there is some variability in pump noise, but it is not understood at this point.

Another pump located upstream of sensor 17 also runs continuously. The noise that it makes is loudest at sensor 17 (which is only 700 ft distant), is

less intense at sensor 18 (which is 1,300 ft farther down the line), and is even less intense at sensor 19 (which is another 1,300 ft down the line). For some reason, the pump noise is not as variable there.

Sensor 20, where one leak was found, is a special case. It is 1,100 ft away from sensor 19, and seems to be picking up a little bit of the pump noise coming from the direction of sensor 17. However, the values from sensor 20 suddenly increased in value between August and December 2005. Also noticed in December was that the ground was wet around a fire hydrant located 30 ft from sensor 20. This fire hydrant had been found to be leaking in September 2004, and Public Works had repaired it late in 2004. Sometime between August and December 2005, the leak had clearly reappeared and was detected by the newly installed PermaLog sensor.

Sensor 16, where another leak was found, is a clearer-cut case than at sensor 20. Sensor 16 is isolated at the end of a dead end 2 in. pipeline, and although it appears to be near sensor 17 when looking at Table 1, in actuality, no sound path connects the two sensors — sensor 16 is acoustically connected only to sensor 15. As can be seen in Table 1, sensor 15 has always been very quiet. The fact that the leak data from sensor 16 have always been 6 to 7 times louder than the leak data received at sensor 15 implies that the 2 in. pipeline has a leak. It was also clear that the leak would be on the far side of sensor 16 from sensor 15, because the leak data at sensor 15 were even fainter than the leak data received by sensor 14.

In June 2006 an AccuCorr leak location instrument was used to investigate the situation at sensor 16. The AccuCorr enables location of a leak's position between two sensors, as described in Appendix E. One AccuCorr sensor (the red one) was placed on the 2 in. pipeline where PermaLog sensor 16 normally resides. The other AccuCorr sensor (the blue one) was placed on a buried shutoff valve 291 ft from sensor 16, in the direction going away from sensor 15. The AccuCorr calculations produced the graph shown in Figure 8, which shows a very sharp peak 5.8 ft from the blue AccuCorr sensor. The Xmic instrument with its ground microphone was then used to listen at a spot over the pipeline 6 ft away from the buried shutoff valve. The sound of leaking water could clearly be heard in the Xmic's headphones.

No water was present on the surface of the ground near the shutoff valve. However, when a flashlight was shone down the vertical riser to the shut-

off valve, it could be seen that water was clearly present at the valve. Because this shutoff valve was located in a secure area, and because there was no surface water present, it is safe to conclude that this leak would not have been discovered if the permanent leak detection sensors had not been installed there.

Equipment issues

Four equipment issues were identified during this project:

1. longevity
2. calibration
3. hardware modifications
4. software modifications.

The longevity of the PermaLog sensors and PermaCom units in the field was a major concern at the start of the project. The battery powered electronic units would be exposed to rain and standing water, 100 degree plus heat, 10 degree cold, lightning, insects, and animals. As the demonstration progressed, the units performed well in these harsh conditions. Some equipment failures did occur for three reasons: (1) improper sealing, (2) connector problems, and (3) improper design. Items (1) and (2) showed up shortly after the installation was completed, while item (3) appeared after a few months in the field and was fixed under warranty.

Shortly after installation was completed, problems appeared in all three of the PermaCom units and in several of the PermaLog sensors. The PermaLog sensor could not communicate to the Patroller unit during a drive-by data collection run. At some sensors, the truck could be stopped, the Patroller disconnected from the rooftop-mounted antenna and taken up to the sensor housing, and the data would come in. At other sensors, however, the data would not come in no matter how close the Patroller came. This problem was finally attributed to water migrating past a faulty seal on the antenna cable into the radio connector on top of the PermaLog. At first the radio signal would merely decrease in amplitude, requiring the Patroller to come closer to receive it. After a while, however, the radio inside the PermaLog would short out, necessitating that the unit be replaced. Replacements of two PermaLog units that failed in this manner were made under warranty.

The PermaCom problems took the form of a complete lack of communication, one from the start and two after a short while in the field. During a visit by the Managing Director of the PermaCom/PermaHost UK manufacturer, it was discovered that one of the PermaCom units had not been properly sealed after its vendor-supplied SIM card had been installed. This allowed water to enter the unit, which quickly destroyed it. The other two PermaCom units had problems with their interface cowls, which sit on top of the PermaLog sensors and communicate via light. It appeared that these cowls had manufacturing defects that also permitted water to enter them. All of these problems were corrected under warranty, and all of the units have been working properly for more than a year.

After several months in the field, two of the PermaLog units started returning peculiar data. Their data value would shoot up to a fairly high level, where it would remain constant. It would also show a very narrow spread value (which is a measure of the width of the noise peak). These two units were replaced, and all of the data values returned to normal. By taking the malfunctioning units apart, it was discovered that the fine silt soil present in some areas of Fort Hood had infiltrated the mechanism that channeled the tiny vibrations from the magnet of the PermaLog into its sensing system. The silt interfered with the channeling mechanism, causing the constant readings. A redesign by the manufacturer has completely eliminated the problem.

The ability of the PermaLog sensors to stay in calibration was also of concern before the start of the project, but the concern proved to be unwarranted. The units are designed to have a 7 – 10 year life in the field, and their internal battery can power them for this entire time period. The PermaLogs also use a fully digital signal path, so no components are subject to drift except for the preamplifier and the analog-to-digital converter. According to the manufacturer, these two components were implemented in integrated circuit form, so the discrete resistors and capacitors that typically cause drift have been eliminated. The manufacturer performs an ongoing test of a number of PermaLogs to check for drift, and they claim that none has occurred over the 4 year period of testing so far.

A number of hardware modifications have been made to the PermaLog and PermaCom units since the project began. These modifications include new antenna seals, new PermaCom unit seals, and new PermaCom cowl seals, as described above. The biggest modifications to be carried out as a

result of this work has been the PermaLog sensing mechanism redesign, to permit the units to operate in the fine silt present at Fort Hood. Since none of the PermaLog units originally installed at Fort Hood had this modification, and since it has turned out to be such a severe problem, the manufacturer is replacing under warranty all Fort Hood PermaLogs that fail in service.

A few software problems were discovered during the project that require modification. The most important of these problems was in the software that the PermaHost cellular telephone data retrieval system comprises. While it works fine, it was not written using standard Microsoft Windows software conventions, as explained in detail in Appendix D. This difference can confuse an experienced Windows user, and cause multiple versions of the program to run at the same time, only one of which is actively collecting data. The other software difficulty experienced was with the documentation for the PermaCom initialization routines. While technically accurate, it was written in a way that a number of people found very confusing — it needs to be rewritten using clearer and simpler language.

4 Metrics

The metrics used for this project included a baseline walkthrough leak survey that was performed 2 years prior to the permanent installation of leak sensors. This survey found approximately 50 leaks, 8 of which were located in West Fort Hood where the permanent demonstration took place. This baseline pattern of leaks is consistent with the approximate age of the water distribution system, the majority of which was constructed in the early 1950s.

Additionally, the data collected from the PermaLog (via the Patroller) were compared against the dataset that was collected using the PermaCom. This dataset comparison was important to ensure the accuracy of the data transmission, due to the added complexity of the transmission path using a PermaCom.

5 Economic Summary

System costs

At the time of this project, an individual sensor cost $325 when purchased 25 at a time. For the flow conditions of the selected demonstration segment, and considering the pipeline consisted primarily of ductile iron, a total of 25 sensors was determined to be suitable for monitoring the 7 miles of pipeline. One sensor is capable of interrogating approximately 500 meters of pipe in both the upstream and downstream directions. A modest overlap of approximately 10 meters was considered a good rule of thumb to ensure good coverage of the entire monitored length.

Cost savings

The PermaLog leak sensors offer the potential to save the Army money, through the timely and accurate detection of leaks in little-traveled areas. During the course of the project, two leaks were discovered by the 25 permanent leak detection PermaLog sensors installed at West Fort Hood.

Four quantities must be considered when determining the cost of a leak:

1. the cost of buying the lost water
2. the cost of treating the lost water
3. the cost of electricity to pump the lost water
4. the cost to repair damage caused to infrastructure by the leaking water.

A calculation of an estimated cost savings for the two leaks that the PermaLog system discovered will be computed when their leak rates are known . Fort Hood DPW has agreed to forward these data when they complete the repairs. Savings that are possible can be illustrated by using figures from the Las Vegas Valley Water (LVVW) district, published in the February 2006 issue of the *Journal of the American Water Works Association*. According to this article, an 8,000 unit PermaLog system discovered 540 underground leaks during a 24-month period. The cost of these leaks to LVVW was calculated at $2,248,500, which was about double the cost to LVVW of running the underground leak survey program. LLVW estimated that the entire cost of the leak detection equipment needed for their project would be recovered in just 4 years of operation.

Additionally, the Army can realize other cost savings through the use of acoustic leak location systems. These savings accrue during the repair process, after a leak is discovered. Traditionally, the existence of a leak is found by surface water appearing on a street or near its edge. A work crew and backhoe are sent to the scene, and an excavation is made to expose the leak in the pipeline. But water seldom appears precisely above a pipeline leak – it can travel for hundreds of feet along the trench line before it surfaces. In such a situation, thousands of dollars can be expended for the crew and equipment to trench along the street to find the leak, repair the leak, and then repair all the damage to the pavement.

The use of acoustic location equipment like the AccuCorr can reduce such repair costs significantly by determining the location of the pipeline leak to within several feet. In this case, instead of the need to trench along the pipe for tens or even hundreds of feet, only a single small hole needs to be dug. A conservative estimate: repair costs can be reduced by 70 percent with the use of an AccuCorr instrument.

Return on investment

OMB Circular A94, Appendix E is used for this return on investment calculation, assuming a 7 percent discount rate. Cost estimates for operation, rehabilitation, and repair are based on American Water Works Association (AWWA) best practices for water infrastructure.

Current leak detection methods for water distribution systems involve expensive and disruptive excavation. The 320-mile water distribution system is projected to require major rehabilitation 17 years from now, at a cost of approximately $21.6 million, as shown under Baseline Costs in Table 3. The existing water distribution system is experiencing widespread leakage, and requires a leak survey and minor repair as soon as possible. The cost of excavation per leak location is on the range of $10,000 – $20,000, not including the costs of repair, decontamination, and site rehabilitation. The total length of the water distribution system is in excess of 300 miles of direct buried piping, and at least 32 excavations would be required to assess the condition and pinpoint leaks. The current practice would incur a cost due to downtime of $200,000 for the year when conventional leak detection takes place and $400,000 for the major rehabilitation period lasting one full year. This represents an avoided cost in the new system/savings in column E of Table 3. This approximate baseline cost avoided for 1 month of impacted flight operations, which require resched-

uling, or moving to a different base, is $33,300. A conventional leak survey for this system takes approximately 6 months, leading to a $200,000 indirect cost impact. Maintenance costs would be incurred annually, for both the baseline and new system. These operating costs, for both the baseline and new system costs are the same, and are not cited on the OMB spreadsheet columns B and D as they cancel each other out mathematically.

By implementing low-cost, near real-time leak detection, the installation can routinely detect leaks as they occur, and at an early stage. Early leak detection will reduce the extent of secondary damage caused by the leakage, limiting the subsequent accelerated corrosion to the piping system by adding electrolyte to the soil surrounding the direct buried piping. With real-time data to detect leaks at an early stage, the useful system life can be extended for an additional 14 years before significant rehabilitation is required. In year 30, the entire system, with leak detection, undergoes extensive rehabilitation at the same cost as the conventional system alone, with $30,000 scrap benefit. Because the system is either undergoing a conventional leak detection and repair (baseline column B) or a major rehabilitation with the new system (column D), there is no indirect benefit for owning the new system, and only the scrap value is listed in column E.

Table 3. Return on investment calculation.

Investment Required			500
Return on Investment Ratio	10.42	Percent	1042%
Net Present Value of Costs and Benefits/Savings	2,848	8,056	5,208

A Future Year	B Baseline Costs	C Baseline Benefits/Savings	D New System Costs	E New System Benefits/Savings	F Present Value of Costs	G Present Value of Savings	H Total Present Value
1	800			230		963	963
2							
3							
4							
5							
6							
7							
8							
9							
10							
11							
12							
13							
14							
15							
16							
17	21,600	30		460	9	6,984	6,975
18							
19							
20							
21							
22							
23							
24							
25							
26							
27							
28							
29							
30	800		21,600	30	2,838	109	-2,729

Direct Costs of Leaking Potable Water Distribution System Include Excavation Costs to Locate the Leak, Leak Repair, and System Decontamination

Number of Excavations Per 10 Miles of Distribution	Number of Miles of Distribution Pipe	Number of Excavations Required	Cost per Excavation	Flushing and Decontamination Costs per leak	Piping Repair and Landscaping Cost Per Leak	Total Cost for System-Wide Conventional Leak Detection
1	320	32	18	5	2	800

Year	Bottled Water for Duration of Downtime Due to Repairs Per 6 Month Period	Estimated Cost per Month of Downtime and/or Relocation Costs for Flight Operations. (Impacted Due to Loss of Fire Supression)	Downtime of Deluge System, and Resulting Interference With Flight Operations, Per 6 Months of Downtime	Avoided Costs, Column E
1	30	33.3	200	230
17	60	33.3	200	460

6 Recommendation

It is recommended that the Army consider installing PermaLog permanent leak sensors at other installations where potable water pipelines run in seldom traveled areas. The PermaLog sensors have successfully proven their ability to detect water leaks at Fort Hood. In addition, according to civilian water utility experience, payback periods are on the order of 5 years for the necessary leak detection equipment.

7 Implementation

It is recommended that this technology be installed at Tri-Service bases as funds are available. In addition, language describing the technology will be inserted to update Unified Facility Guide Specifications (UFGS) and Technical Manuals (TM) for operation of potable water systems, as well as heating and cooling distribution systems. Some guidance that is recommended for update with the results of this project include: UFC 3-230-08A, "Design: Water Supply: Water Treatment," UFC 3-401-01FA, "Design: Utility Monitoring and Control Systems," UFC 3-420-01, "Design: Plumbing Systems," UFGS 11145, "Aviation Fueling Systems," UFGS 13801, "Utility Monitoring and Control System (UMCS)," UFGS 15181, "Chilled, Chilled-Hot and Condenser Water Piping Systems."

Additionally, it is recommended that this technology be included in the Installations Design Standards maintained by the Technology Standards Group.

8 Conclusions

Twenty-five permanent leak detection sensors were successfully installed on about 7 miles of potable water pipelines in West Fort Hood. Specific conclusions are as follows:

1. The PermaLog leak sensors installed at West Fort Hood have proven that they can detect water leaks, including leaks where water never rises to the surface. Two separate leaks, one totally hidden from view that probably would have remained hidden without the use of the PermaLog system, were discovered.
2. A detailed procedure has been developed for determining suitable sensor locations, finding pipelines, and installing sensor housings that will not interfere with data collection.
3. Two separate methods of retrieving the leak data were developed, and methods were developed for analyzing the data to find leaks.
4. A number of lessons were learned about some installation and operation pitfalls that will be beneficial to others that undertake the installation of permanent sensors on pipelines at other Army installations.

Payback periods for purchasing the necessary leak sensor equipment, according to civilian water utility experience, are on the order of 5 years.

Appendix A: Leak Sensor Position Maps and Coordinates

The following maps show the positions of all 25 PermaLog leak sensors installed at West Fort Hood during the project. The maps start with a broad overall view of the entire leak sensor layout, shown in Figure A1. Then three broad views of about one-third of the system per view are shown in Figures A2 – A4. Finally, six close-up views of about one-tenth of the system per view are shown in Figures A5 – A10.

Table A1 at the end of this Appendix shows the coordinates of the PermaLog sensors in two different ways. The first, Easting and Northing, are used with the electronic Fort Hood GIS map coordinate system. The second, Longitude and Latitude, are used with handheld GPS devices in the field.

Figure A1. An overall view of all 25 leak sensors in West Fort Hood.

Figure A2. A broad view of leak sensors 1 – 6 in West Fort Hood.

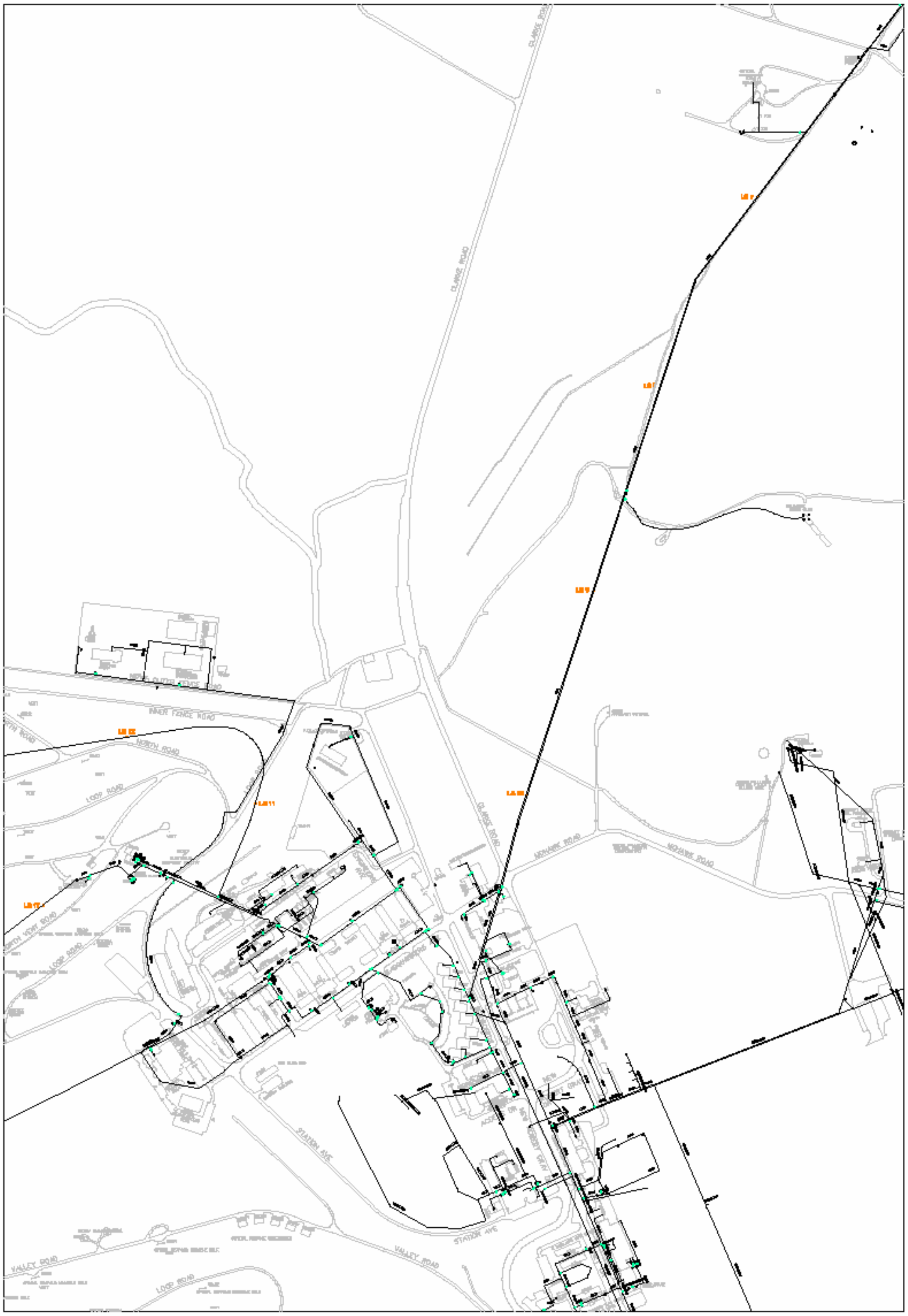

Figure A3. A broad view of leak sensors 7 – 12 and 17 in West Fort Hood.

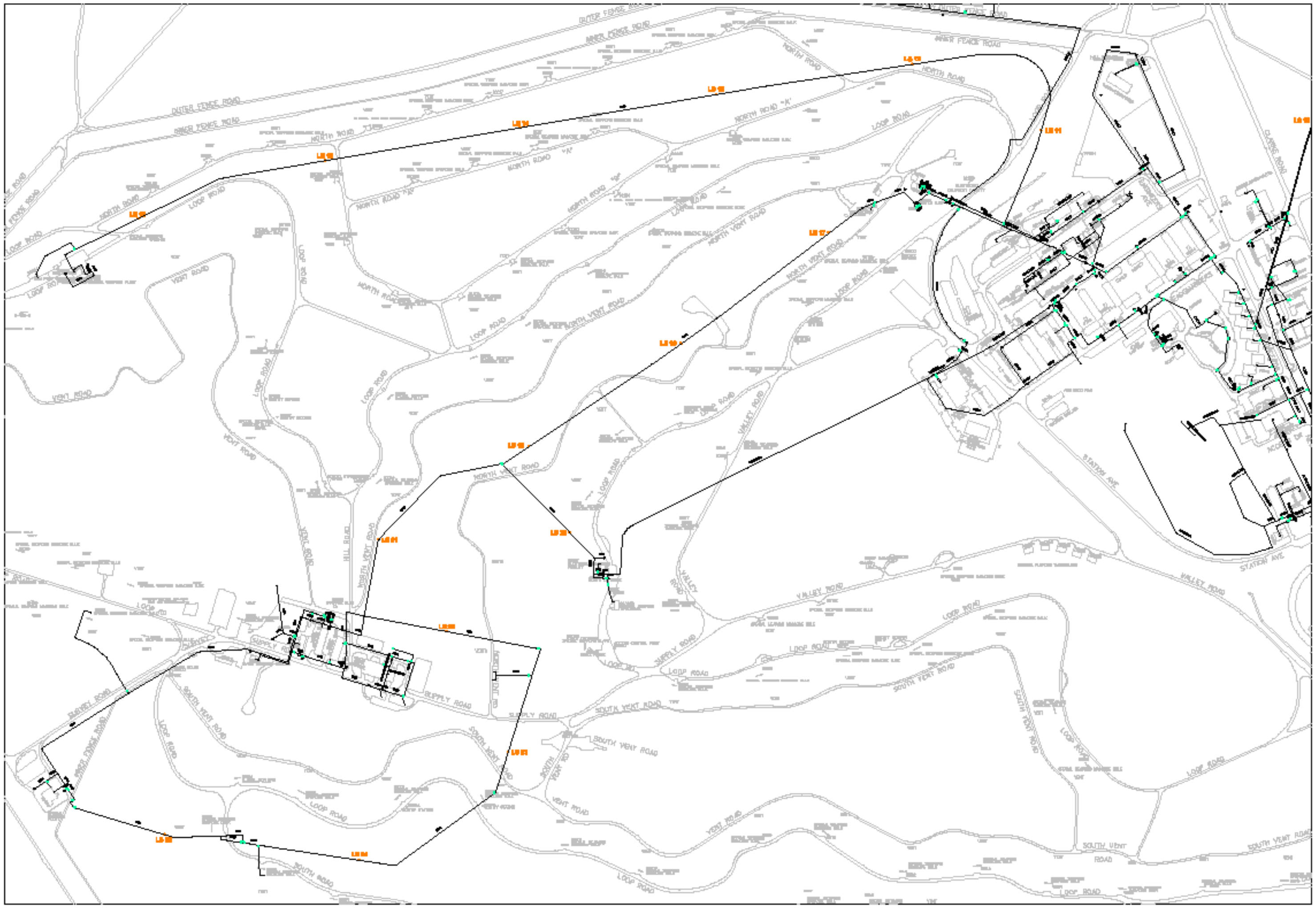

Figure A4. A broad view of leak sensors 10 – 25 in West Fort Hood.

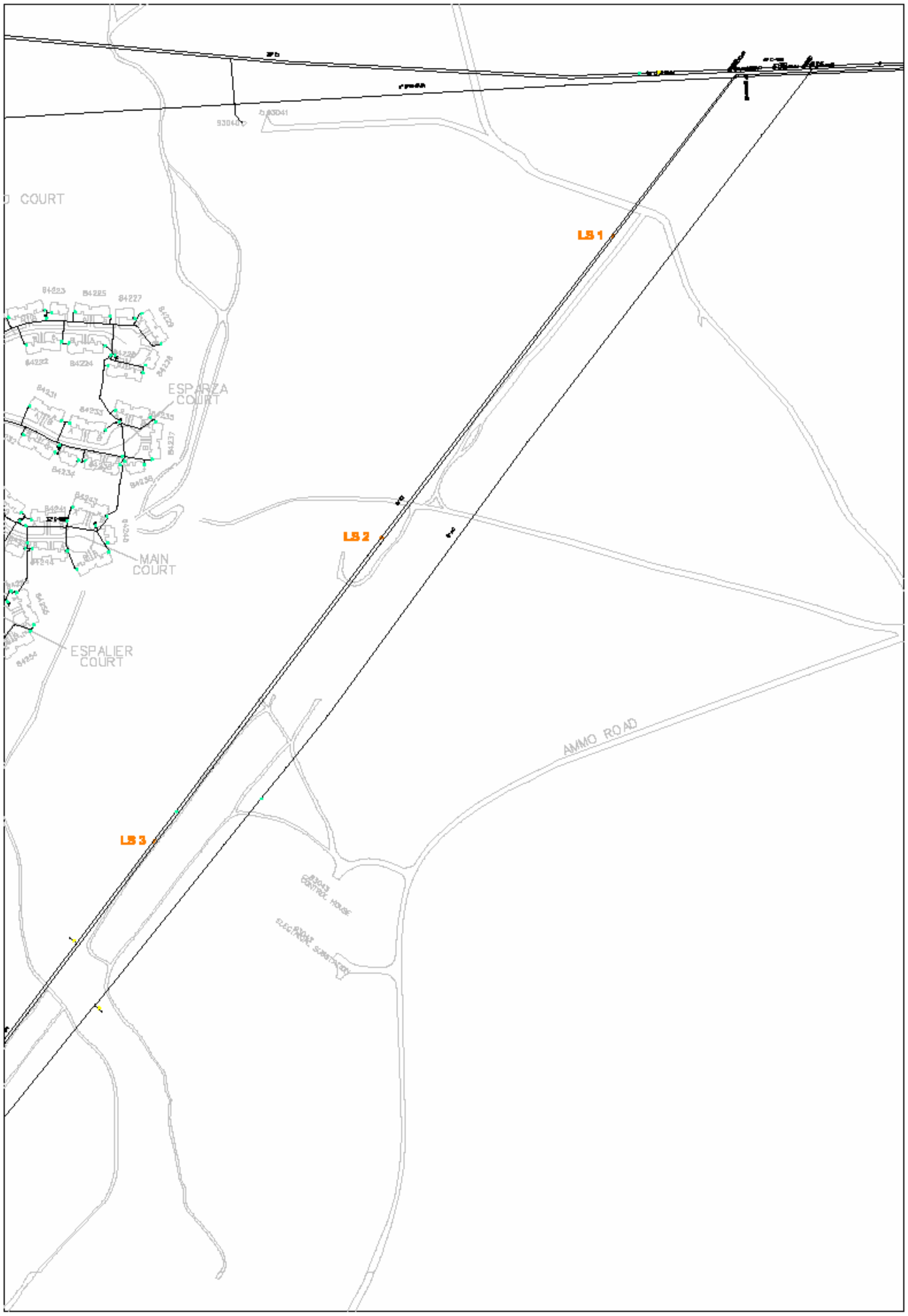

Figure A5. A close-up view of leak sensors 1 – 3 in West Fort Hood.

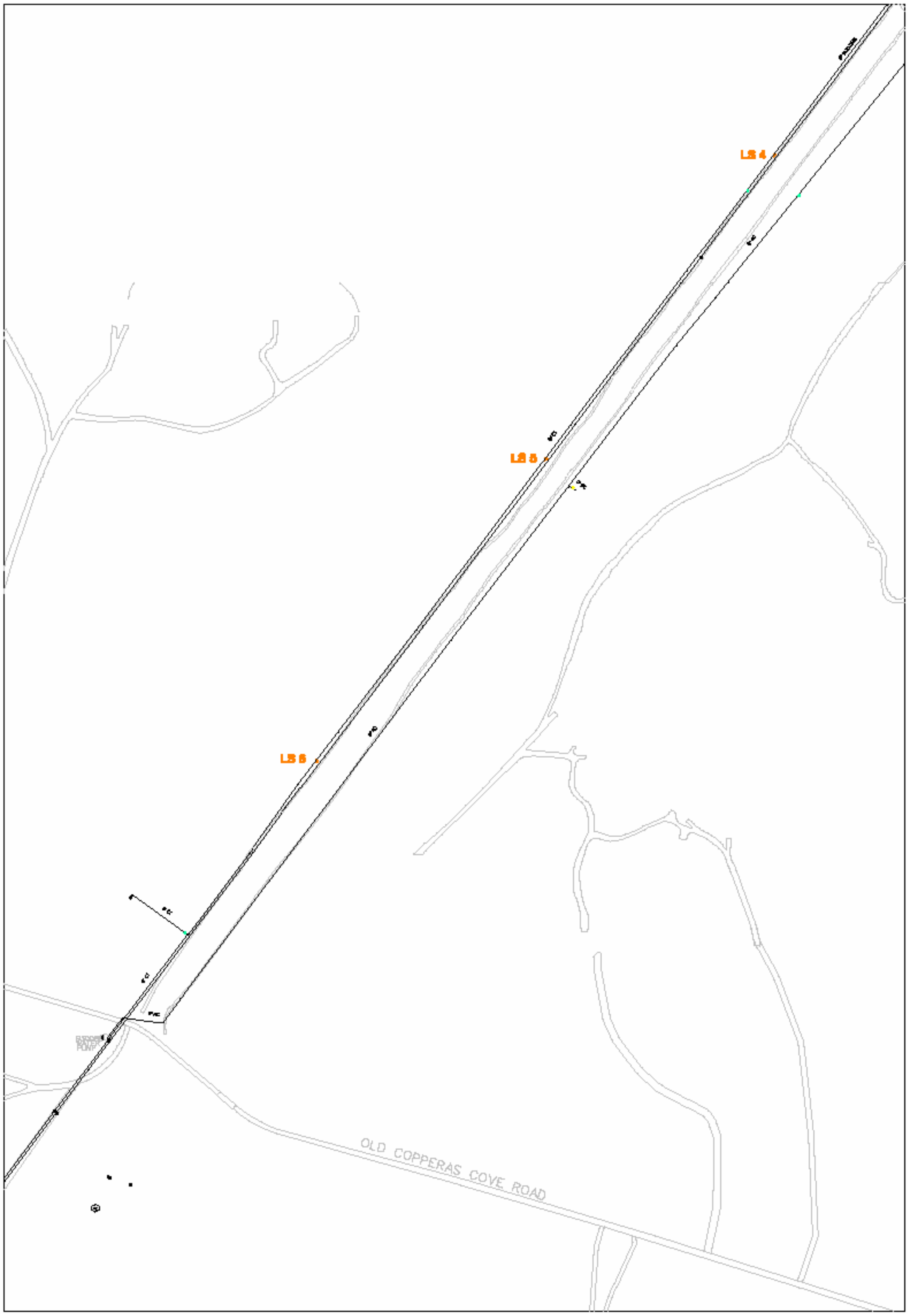

Figure A6. A close-up view of leak sensors 4 – 6 in West Fort Hood.

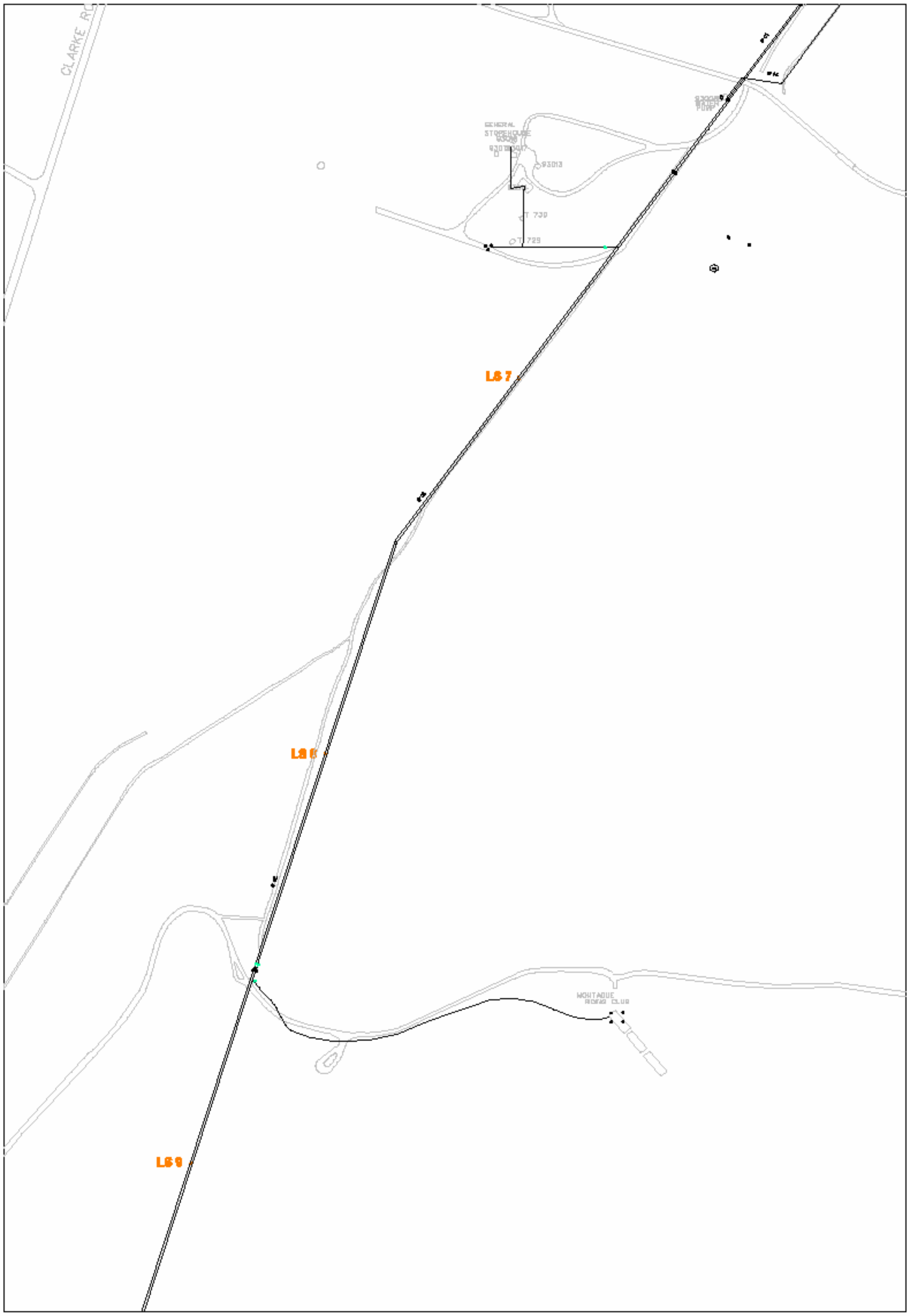

Figure A7. A close-up view of leak sensors 7 – 9 in West Fort Hood.

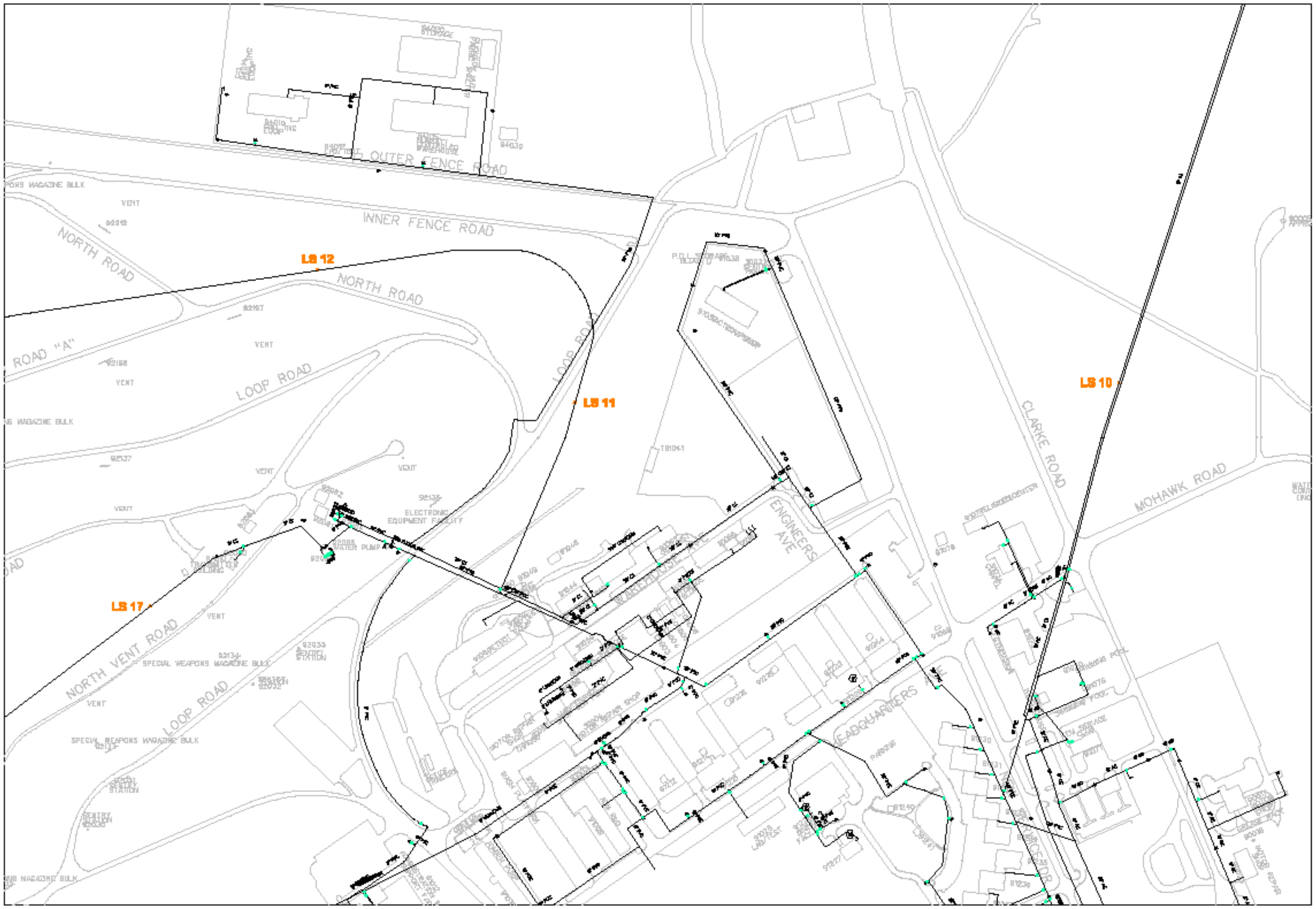

Figure A8. A close-up view of leak sensors 10 – 12 and 17 in West Fort Hood.

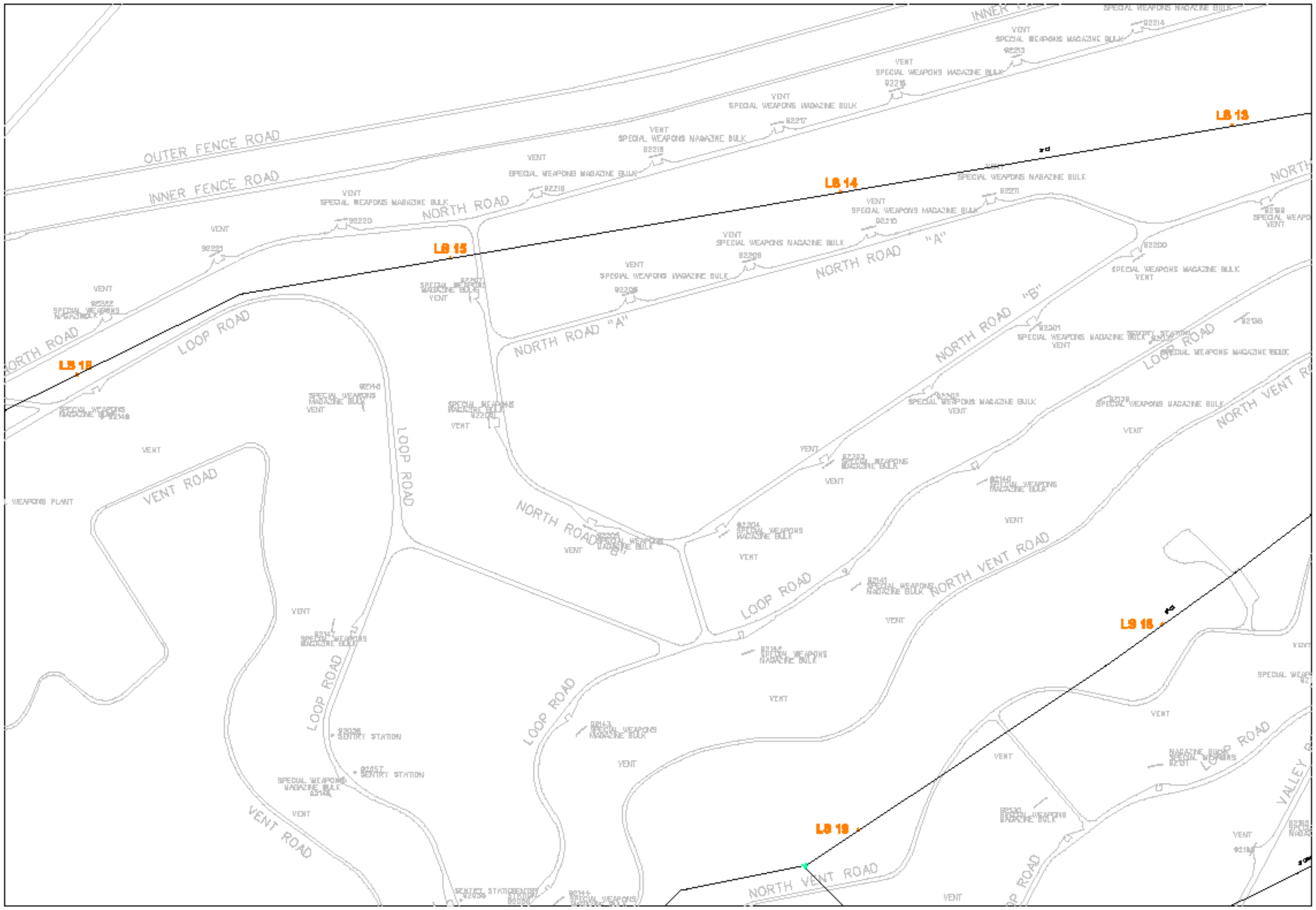

Figure A9. A close-up view of leak sensors 13 – 16 and 18 – 19 in West Fort Hood.

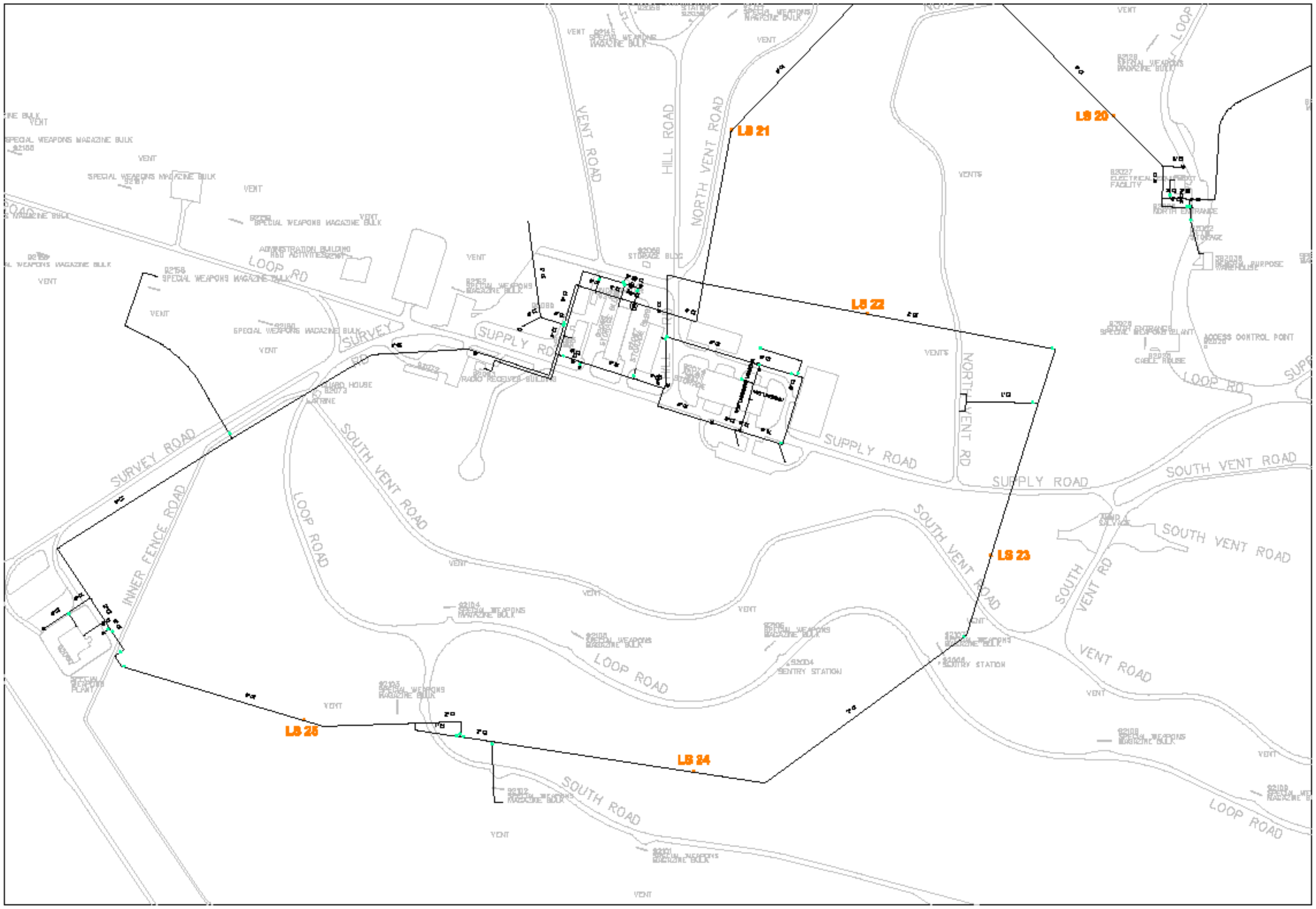

Figure A10. A close-up view of leak sensors 20 – 25 in West Fort Hood.

Table A1. Location Coordinates for the 25 Leak Sensors.

Sensor ID	Easting	Northing	Longitude	Latitude
LS 1	612737 m	3443093 m	97 49 03.7W	31 6 58.7N
LS 2	612494 m	3442776 m	97 49 13.0W	31 6 48.5N
LS 3	612254 m	3442456 m	97 49 22.2W	31 6 38.2N
LS 4	612014 m	3442137 m	97 49 31.3W	31 6 27.9N
LS 5	611774 m	3441818 m	97 49 40.5W	31 6 17.6N
LS 6	611532 m	3441500 m	97 49 49.8W	31 6 07.4N
LS 7	611093 m	3440914 m	97 50 06.6W	31 5 48.5N
LS 8	610890 m	3440518 m	97 50 14.4W	31 5 35.7N
LS 9	610749 m	3440089 m	97 50 19.9W	31 5 21.8N
LS 10	610609 m	3439660 m	97 50 25.4W	31 5 07.9N
LS 11	610037 m	3439640 m	97 50 46.9W	31 5 07.5N
LS 12	609765 m	3439779 m	97 50 57.2W	31 5 12.1N
LS 13	609352 m	3439715 m	97 51 12.8W	31 5 10.2N
LS 14	608940 m	3439646 m	97 51 28.3W	31 5 08.1N
LS 15	608530 m	3439576 m	97 51 43.8W	31 5 05.9N
LS 16	608136 m	3439453 m	97 51 58.8W	31 5 02.1N
LS 17	609590 m	3439425 m	97 51 03.9W	31 5 00.7N
LS 18	609279 m	3439191 m	97 51 15.7W	31 4 53.2N
LS 19	608959 m	3438975 m	97 51 27.9W	31 4 46.3N
LS 20	609044 m	3438792 m	97 51 24.8W	31 4 40.3N
LS 21	608643 m	3438778 m	97 51 39.9W	31 4 40.0N
LS 22	608785 m	3438584 m	97 51 34.6W	31 4 33.6N
LS 23	608915 m	3438330 m	97 51 29.8W	31 4 25.3N
LS 24	608602 m	3438102 m	97 51 41.7W	31 4 18.0N
LS 25	608192 m	3438157 m	97 51 57.1W	31 4 19.9N

Appendix B: Drive-by Data Collection Procedure

Drive-by data collection takes about 30 minutes to complete, and is performed using the Patroller instrument – a hand-held device that retrieves the PermaLog sensor data. It is designed to be taken by vehicle close to all of the PermaLogs, and it will retrieve their data automatically via a radio link.

The Patroller is placed on the passenger seat and attached to the vehicle power outlet. To do this, insert one end of the power adapter cable into the Patroller (using the small connector on the right hand side with three pins), and plug the other end of the power adapter cable into the vehicle power outlet itself.

The range of the Patroller is greatly extended through the use of an external antenna, which mounts magnetically to the roof of the vehicle. After the antenna is mounted in the center of the roof, feed the antenna cable through a door (being careful that the cable will not be damaged when the door is closed). Attach the antenna cable to the Patroller using the BNC connector on the top side of the Patroller.

Refer to the map shown in Figure C1 for the route that needs to be driven. As can be seen, the route starts at the eastern edge of Copperas Cove, in the Wal-Mart parking lot. Turn on the Patroller at this point, while the vehicle is stopped, by depressing the button on the left hand side until a beep is heard. Now look at the top right hand corner of the LCD screen. If a dot and three curves are seen, then you are in high power mode and all is well. If the dot and three curves are not seen, then press the Esc button, then the 2 button, then the 1 button. Now press the Esc button, then the 1 button, and the dot and three curves will now be seen on the LCD.

Start driving towards the West Fort Hood gate at the southern end of Constitution Drive. Keep the speed of the vehicle around 30 mph (to give the radio link plenty of time to retrieve the data). You will start to hear various beeps coming from the Patroller as you get onto Fort Hood property, which means that the Patroller is communicating with various PermaLogs. The ID numbers of the PermaLogs that have sent their data can be seen on

the bottom of the LCD screen of the Patroller. By using the up and down buttons, you can move the highlight on the screen from one sensor to another to check the IDs for other sensors.

The first critical point on the drive is just about 1 mile after the cattle guard inside the gate. It is at the top of a small hill on the paved road, where a dirt road crosses the paved road. At this spot it is critical to obtain the data from LS16. Most of the time, it is sufficient to pull off to the right of the paved road onto the dirt cross road and wait for a few minutes. Sometimes, however, it is necessary to drive south on the dirt road for about a mile before the LS16 data will come in. **Note that it is absolutely necessary to get the LS16 data before leaving this point, as this is the only spot on Fort Hood where the data from LS16 can be received.**

Once the LS16 data have been received, continue driving along the paved road, go through the security check, and make a left onto Clark Road. Then make a right onto Copperas Cove Road. Take this road almost to the point where you go through the security gate, and make a left onto the dirt road. Follow this dirt road about a mile until you get to the electrical station on the left, and use the second driveway past the cattle guard to get to the parking area just north of the electrical station.

This is the second critical point on the drive, and it is necessary to get the data from LS1, LS2, and LS3 here. Most times they come in before you get to the parking area, or after just a minute or so. Sometimes, though, it is necessary to get back on the dirt road, make a left and go north until you get to the fenced area around the valve nest. **Note that it is absolutely necessary to get the LS1, LS2, and LS3 data before going south of the electrical station on the dirt road, as this is the only spot on Fort Hood where the data can be received.**

Once the LS1, LS2, and LS3 data have been received, drive back along the dirt road until you see a yellow left curve sign on the right side. About 100 yards past this yellow sign is a rough track to the right, going around to the west side of the hill. Follow this track about 50 yards to a turn-around area and stop. At this point, you should have received the data for LS4 and LS5.

To check to see which sensors the Patroller has not received data from yet, hit the Esc button, then the 2 button, then the 5 button. Use the up and

down arrow buttons to highlight the FTHOOD line, and then press the Ent button. All of the sensors that have not sent data to the Patroller will now be listed on the LCD screen; you can use the up and down arrow buttons to note their IDs. **At this point in the patrol, it is important that sensors LS1 through LS8 do not appear on the screen.** Once you have assured yourself that they do not, press the Esc button, press the Esc button again, and then press the 1 button. Check to be sure that the dot and three curves are seen at the top right of the LCD screen; if they are not, then re-establish High Power mode as explained previously.

Now get back on the dirt road and head south away from the electrical station. When you get to Copperas Cove Road turn right. At Clark Road, turn left. After about a mile, as you come up a small hill, you will see the road widen. Make a right onto Loop Road just past the chain link fence; follow Loop Road around as it bears to the left, and you will start going up a hill. Just beyond the large bare area on the right, make a right onto Loop Road. Follow this road as it bears to the left, beyond North Road on the right and Vent Road on the left. Keep following Loop Road past the fenced in area on the right. As you start to go up a steep hill, the road name will change to Hill Road. Just before you reach a stop sign, you must see the data from LS21 come in. At the stop sign, make a right onto Supply Road. Drive down to the point where the water tower is on the right, turn around and stop.

This is the third critical point on the drive, and it is necessary to wait here a bit to see if the data from LS25 comes in. If it does, fine, but if not then just drive slowly down Supply Road past Hill Road, and stop just beyond the end of the buildings where a dirt road appears on the left. At this point, it is necessary to wait until the data from LS22, LS23, LS24, and LS 25 come in. Most of the time this data will appear as you drive slowly down Supply Road, but sometimes it is necessary to turn around and drive slowly back to the water tower and then back to this point. **Note that it is absolutely necessary to get the LS22, LS23, LS24, and LS25 data before leaving this stretch of road, as this is the only spot on Fort Hood where the data can be received.**

Once the LS22, LS23, LS24, and LS25 data have been received, drive down Supply Road away from the water tower. Near the bottom of the steep hill, make a sharp left onto Loop Road. Drive slowly along Loop Road. Somewhere on this drive you should get the data from LS18 and LS19, if they

have not been received already. When you come to a stop sign, make a left. It will be marked Valley Road, but you will still be on Loop Road — follow it until it stops at Clark Road. Make a left onto Clark Road, and then pull over onto the wide paved shoulder of the road just past the chain link fence.

Now perform the missing sensor check, as described previously. If everything has gone smoothly, no sensor numbers will be listed on the Missed Logger List screen. If a sensor is missing, however, it will be necessary to drive back near its position (sometimes right next to the sensor box itself) until its data are received. This does not happen often, but can happen occasionally on rainy days because radio reception seems to be poorer than on sunny days. This also had to be done after the antenna cable kinked and developed an electrical problem. A spare antenna cable has been provided as a replacement, to cover this case.

Once data have been acquired from all 25 sensors, turn off the Patroller by depressing and releasing the silver button on the left. Disconnect the power cable from the vehicle power outlet, and then disconnect the power cable from the Patroller. Now disconnect the antenna cable from the Patroller and the antenna. Put the Patroller in its slot in the Pelican case, coil up the two cables and put them in the case as well.

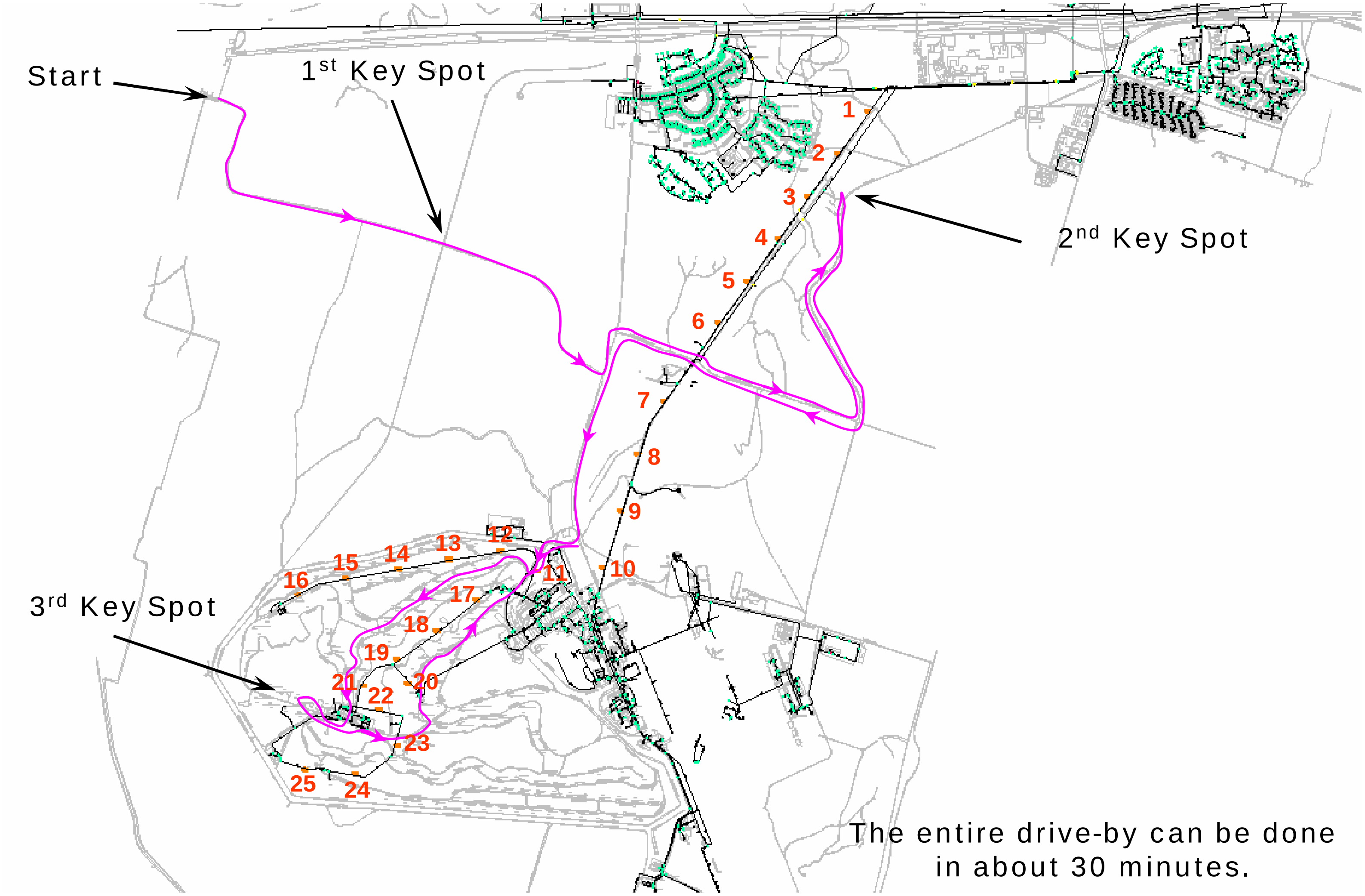

Figure C1. A map showing the route for drive-by data retrieval at West Fort Hood.

Appendix C: Loading the Drive-by Data onto the Computer

Bring the Patroller to the central data computer. Locate the two serial ports on the back top left edge of computer and attach the serial data cable's beige plug to the bottom of the two serial ports that are available. Attach the silver end of the serial data cable to the large connector on the right side of the Patroller by matching the red dots on the cable and the connector and pushing.

Bring up the PermaLog program screen on the computer and ensure that data from the last patrol are displayed (check the patrol dates to verify). Now turn on the Patroller by depressing the silver button on the left hand side until a beep is heard. When the data screen appears, press the Esc button, then the 4 button. You should now see a screen that mentions packets, retries, and records (if it says "PC is not connected, check the serial data cable connections" and try again).

In the PermaLog program, click on the Patroller menu item up top; highlight Receive from Patroller, and then click on Selection. You will see a box labeled Receive DMAs in Patroller, and packets will be received. Click OK when the blue progress bar stops moving. Now put a check mark in the FTHOOD.pdb box, click OK, and the patroller data will open in a new window. Click on the File menu item up top, click Save As, and give it the next name in the INSTALLXX.csv list, where XX are sequential numbers. The correct numbers to use will be clear from the list of files shown in the window on the computer screen (select numbers to make the files sequential).

Finally, press and release the silver button on the left hand side of the Patroller to turn it off. Disconnect the serial cable from the Patroller by pulling on the ridged portion of the connector, and disconnect the other end of the serial cable from the computer. Put the Patroller in its slot in the Pelican case, coil up the serial cable and put it in the case as well.

Appendix D: PermaHost Program Issues

The PermaHost program, which is the program on the central data computer that collects the leak data automatically from sensors LS9, LS15 and LS22 using the cellular telephone network, does not behave like a standard Windows program.

The first trick is how it reveals if it is indeed running. Unlike a standard Windows program, if it has been minimized it will not be listed on the Task bar. Instead, an icon will appear in the area of the Task bar where the date and time are shown. This icon, which is mainly white with a blue v-shaped line through it, must be double clicked to restore the PermaHost program.

It is ***extremely*** important to always check for the presence of this icon before attempting to run the PermaHost program from the start menu or the desktop icon. Unlike a standard Windows program, you can easily start duplicate PermaHost programs – except that these extra instances will not initialize correctly and will not collect data. If you look at the lower right corner of a PermaHost program window and you do not see any blue bars after the words Incoming Modem Signal and Outgoing Modem Signal, you can be sure that this is an extra instance of the program.

To kill these extra instances, you need to know the second trick. Unlike a standard Windows program, clicking on the red X at the top right of the PermaHost program window does not stop the PermaHost program — it just minimizes it and creates another icon near the date and time as described above. The only way to stop the PermaHost program is to click on File in the menu bar, and then click on Exit. This will bring up a box that asks if you are sure — click on Yes and this particular instance of the PermaHost program will stop. Repeat as necessary until only one instance of the PermaHost program is running. You can maximize this primary instance by double clicking on the icon, verify that it is the primary instance by looking for the blue bars after the words Incoming Modem Signal and Outgoing Modem Signal, and then you can view the leak data normally.

Appendix E: Acoustic Leak Location Procedure

Detecting leaks in pipelines with acoustics involves a fairly straightforward process. A special instrument with a highly sensitive microphone is placed on valves and other objects that connect directly to the pipeline being surveyed. A leak in the pipeline reveals itself by the sounds that the water, fuel, or air inside the pipe makes as it escapes. A generalized location of the leak can be determined by moving the microphone from valve to valve along the pipeline until the loudest noise is received. After that, a specialized microphone can be used on the ground above the pipeline along its length to obtain a better idea of the position of the leak.

To precisely locate a leak in a pipeline, it is necessary to determine a time difference, using the following five steps:

1. Position two sensors so that they bracket (surround) a possible leak. If the sensors do not surround the leak, the leak *cannot* be located, no matter what signal processing method is used. (Only leak *detection* can be accomplished if the sensors do not surround the leak.)
2. Acoustically couple the sensors to the pipe so that both sensors receive distinct leak signals. Leak location cannot be performed without signal arrivals at *both* sensors. This step implies that quick, reproducible methods exist to acoustically couple sensors to pipes in the field.
3. Measure the distance between the sensors, *D*, and determine the velocity of sound in the media contained in the pipe, *V*.
4. Use signal processing (coincidence detection, cross-correlation, etc.) to determine a time difference, Δt, for the arrival of a specific signal feature at both sensors.
5. Using the time difference (Δt) obtained in Step 4, calculate the location of the leak using the following equation:

$$\text{Location from first sensor detecting signal} = (D - (V\,\Delta t)) / 2$$

Note that to successfully locate leaks it is absolutely necessary to (1) ensure that the sensors are on the correct pipe, (2) know the length, material, and diameter of the pipe being monitored (in order to calculate the speed of sound in the media contained in the pipe), and (3) know the exact distance

along the pipe between the sensors. The piping system owner is depended upon to provide this data accurately (in the form of maps and tables) so that the location calculated will be as accurate as possible (and Fort Hood did indeed provide such information).

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Thousands of miles of direct-buried water distribution lines are subject to severe corrosion at almost all U.S. Army installations. Leakage of storage tanks and piping systems has been identified as a mission-critical problem. To demonstrate acoustics-based leak-detection technology for the Department of Defense (DoD) Corrosion Protection and Control (CPC) Program, permanent acoustic leak-monitoring sensors were installed on potable water lines at Fort Hood, Killeen, TX, during 24 April – 31 May 2005.

As a result of this work, 25 permanent acoustic leak detection sensors now monitor about 7 miles of potable water lines in remote, little traveled areas, where a water leak would not likely be discovered for a very long time. To retrieve the leak status from the 25 sensors, one method is to use a special radio receiver that can be driven past the sensors periodically, and the other is to use a central computer equipped with cellular telephone modems that retrieve the data automatically.

A few problems were experienced during the project, but all were success-fully solved. During the project, lessons were learned about some installation and operation pitfalls that will benefit others who undertake the installation of permanent sensors on pipelines at other Army installations.

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